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ECONOMIC IMPACT OF STIMULATED TECHNOLOGICAL ACTIVITY

Part I - Overall Economic Impact of Technological Progress--Its Measurement

FINAL REPORT
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PREFACE

This is one of five volumes which present the findings of a research inquiry into the Economic Impact of Stimulated Technological Activity. The titles of the volumes are:

Part I - Overall Economic Impact of Technological Progress--Its Measurement

Part II - Case Study--Technological Progress and Commercialization of Communications Satellites

Part III - Case Study--Knowledge Additions and Earth Links from Space Crew Systems

Summary Volume--Economic Impact of Stimulated Technological Activity

Bibliography

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The findings and judgments expressed in the report are those of the MRI project team and do not necessarily reflect the view of the National Aeronautics and Space Administration or those of any company or individual surveyed.

Approved for:

MIDWEST RESEARCH INSTITUTE

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22 November 1971

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OVERALL ECONOMIC IMPACT OF TECHNOLOGICAL PROGRESS--MEASUREMENT

"The nation's technological capacity, which is conceptually analogous to the capacity of its physical plant, is unquestionably a nation's most important economic resource. By the same token, the rate at which its technological capacity grows sets what is probably the most important ceiling on its long-term rate of economic growth.

The rate of growth of a nation's technological capacity depends jointly upon the rate at which it produces new technology and the rate at which it disseminates the old."

Jacob Schmookler
Invention and Economic Growth
1966

I. INTRODUCTION

The central questions toward which this phase of the report is addressed are:

1. What is the role of technological progress in national economic growth?

2. What factors determine the rate of economic growth due to technological progress?

3. Can the relationships between technological progress, its determinants, and subsequent economic growth be measured--quantitatively?

4. And, how do the research and development activities of the space program tie into the preceding questions?

Before World War II, there was little need to ask such questions at the national level. Most development was performed by the hallowed individual inventor or by industrial laboratories supported by company funds. Choices as to whether or not to allocate resources to development and how to distribute resources among projects were made within individual companies. Most of the nation's research effort was performed at universities as an adjunct to graduate education. National priorities had little direct influence on the allocation of resources to R&D, and the scale of

Part I

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R&D was small enough that the formulation of precise relationships between R&D and the economy lacked urgency. In addition, economists as well as political and business leaders were too preoccupied with the effects of the Depression and the implications of Keynesian economics to devote more than passing attention to R&D.

R&D grew dramatically following World War II under the stimulus of the Cold War and the race to combine atomic weapons with rocketry. Massive mission-oriented R&D programs were mounted, using as their model the Manhattan Project of World War II. All facets of research--basic and applied--as well as development and sophisticated production plus scientific and engineering education underwent huge federally funded expansions. A strong scientific and technological capability became an essential instrument for national survival--decisions to allocate resources to R&D were made on the basis of necessity. The economic effects of the consequent shifts of resources to highly technological endeavors were judged to be positive, but were not critical factors in the national decision-making process.

By the late 1950's, when the nation's first massive civilian mission-oriented R&D agency--NASA--was created, the economic effects of such undertakings were receiving explicit, if imprecise, recognition. At about the same time, the short-term and regional economic impacts of expanded R&D began to receive widespread recognition. Community after community strove to become another Route 128, or San Francisco Bay Area, or Huntsville. The immediate benefits of a local R&D complex were clear. Less clear were the processes whereby R&D led to new or improved processes, products, and services. But more important to the purposes of the present portion of this report, the theory, methodologies and empirical data needed to quantitatively measure the cumulative effect over time of the product and process advances were sadly deficient.

During the 1960's, a number of theorists and researchers undertook to improve our ability to measure the economic impact of technological advances, for it had become clear that technology was a large and powerful force in the accumulation of national wealth. Pioneering work by Solow, Kendrick and Denison was amplified and extended by a number of others. Much progress has been made, but the fact remains that we got to the moon in a decade, but are, as yet, unable to fully measure the present and future economic impact of the science and technology accumulated on the way to the moon (or the aggregate effect of technological progress in general). Our present capability to measure the relationship between technological progress and R&D is even less precise.

Yet, national decisions with respect to the allocation of resources to and within R&D are being and will be made. These decisions cannot be postponed until precise measurements of their effects are possible. Thus, the intent of this study was to provide--from within the existing state of the art--some measurements of technology's contribution to this nation's wealth during recent years and the role of R&D in generating growth through technological progress.

II. RESEARCH APPROACH

The investigations were performed at the national economic level. We were exploring the aggregate effects of technological progress rather than those stemming from individual inventions or innovations. Inadequacies in all existing macro-economic yardsticks forced the study to focus on the "cost savings" effects, i.e., increases in the productivity of labor and capital achieved through technological progress. The many improvements in the quality of goods and services due to research and development are not adequately reflected in existing aggregate economic series and cannot be directly measured.

Given these restrictions on the scope of the study, six research tasks were performed:

First, we adopted a definition of technological progress that is consistent with how progress occurs and how it is generally perceived to occur. In this definition we make a distinction between the technologist's concept and that of the economist in viewing technological progress. Our emphasis, of course, is on the economic impacts and we, therefore, favor the economist's concept.

Second, within the framework of the definition of technological progress and neo-classical economic growth theory, a suitable macro-economic production function was structured.

Third, a technology index implicit in the production function specification was used to quantitatively assess the impact of applied technology on economic growth and output.

Fourth, having determined the level of technology and resulting output, we related technological progress generating activities such as research and development, economies of scale, education, etc., in a mathematical model. Here, the determinants of technological progress were linked to the effect of their stimulus in terms of incremental economic output.

Fifth, through the use of statistical analysis, we empirically determined quantitative relationships existing between growth due to technological progress and determinants of technological progress.

Sixth, within the preceding analytical framework, we examined the economic impact associated with the technological stimulus provided by the space program.

III. SUMMARY OF FINDINGS AND CONCLUSIONS

This chapter synopsizes the major findings and conclusions developed during the course of our investigation of the role of technological progress in the growth of the U.S. economy between 1949 and 1968. The analytical methodologies, research procedures, assumptions, and the underlying rationales for each are presented in detail in subsequent chapters and appendices.

As have others before us, we found technological progress has been a powerful force in economic growth. Our study considered:

- that technology is one of the factors of production--along with labor and capital--with which the output requirements of the nation are satisfied;

- that what we term technological progress is responsible for improvements in the quality or productivity of labor and capital;

- that technological progress results from the introduction of new or previously unused knowledge into the production process;

- that there are many mechanisms by which knowledge is productively applied, including: improved worker skills, improved machine design, improved management techniques, and so on.

Measuring the effect of technological progress--so defined--during the 1949 through 1968 time period, we found that:

- The technology added to the nation's production recipe after 1949 accounted for 40 percent of the increase in private, non-farm output during the period.

- Cumulatively, total output for the period was about $8.2 trillion in constant 1958 dollars. If there had been no increase in the level of technology after 1949, the stock of labor and capital applied would have only yielded a cumulative output of $6.9 trillion. Thus, the leverage on the other two factors of production by technological progress permitted almost 20 percent more output than might otherwise have been achieved with the same quantity of labor and capital.

- Throughout the period the importance of the technology factor in the production function increased at a compound rate of 1.7 percent per year. By the end of the period--in 1968--the compounding growth of technology had reached a point at which technological improvements beyond 1949 levels were accounting for 37 percent of output.

Although it is possible to dissent on very valid grounds about the exact amount of productivity gains due to technology, the major conclusion is clear. Without the increase of technology and its introduction into the production recipe, this nation would be substantially less wealthy than it is. Much of the economic wherewithal we are now attempting to apply toward the solution of pressing domestic problems is the product of applied technological progress. To maintain and expand this economic capacity for problem resolution, this nation must continue to allocate resources to enterprises which generate technological progress and encourage its productive utilization.

This brings us to the second set of findings--those related to the sources or determinants of technological progress. The theoretical and empirical foundation for these assessments is less definitive than for the preceding findings. However, there is general agreement on a list of forces important in the generation of technological progress. The forces are highly interactive but, for analytical reasons, were treated independently. Our findings indicated that most of these forces were of insignificant effect during the relatively short time period under study. However, three factors--the sex mix of the workforce, education, and R&D--were found to be important determinants of economic gains through technological progress during the Post-World War II period. The first, sex mix, is the product of increasing participation by females in the workforce and increasing productivity by distaff employees. Improvements in this factor during the period were put at 4 percent of the gains due to technology. Improved worker productivity through higher educational levels contributed approximately 36 percent. The balance of the technology-induced gain--60 percent--was attributed to R&D because other possible determinants had no measurable, or identifiable, impact.

The relationship between R&D- and technology-induced economic gains was explored on a distributed-lag basis. Lag distributions between R&D expenditures and initial pay-back and final pay-out in the form of national economic gains were constructed from less than definitive industry estimates and experience, but when subjected to statistical tests the relationships exhibited reasonably good explanatory power. The findings were that--on the average--each dollar spent on R&D returns slightly over seven dollars in technologically induced economic gains over an 18-year period following the expenditure.

This finding leads to the strong conclusion that, on the average (including good, bad, and indifferent projects), R&D expenditures have been an excellent national investment.

The final set of findings relates to the economic impact--via technological progress--of NASA's R&D programs. Assuming that NASA's R&D expenditures had the same pay-off as the average, we found that the $29 billion spent on civilian space R&D during the 1959-1969 period has returned $56 billion through 1970 and will continue to produce pay-off through 1987, at which time the total pay-off will have been $207 billion. The discounted rate of return for this investment will have been 33 percent per annum.

As noted, the preceding finding was based on the assumption that NASA R&D spending has an average pay-off effect; there is strong preliminary evidence that the exacting demands of the space program may produce greater than average economic effects due to technological leverage. This comes about because NASA allocates its R&D dollar to the more technologically intensive segments of the industrial sector of the economy. The weighted average technological multiplier of the industries which perform research for NASA is 2.1, while the multiplier for all manufacturing is 1.4. Although there are a number of conceptual and procedural limitations to the construction of industry-level technological multipliers, the spread seems large enough to support the view that highly technological undertakings, such as the space program, do exert disproportionate weight toward increased national productivity.

IV. FACTORS THAT INFLUENCE ECONOMIC GROWTH

Introduction

Per capita income or product is, as a practical matter, probably the best single summary or surrogate measure by which to determine whether and how much economic growth has occurred. Once the fact and amount of growth have been documented, we can then proceed to explore how and why that growth of total product has taken place.

Unfortunately, the list of factors which have some recognizable influence on growth is lengthy.1/ What seems needed, then, is to start with the central or nucleus determinant, and add other significant influences as they can be defined and quantified.

Labor Inputs. One convenient starting point is the expression,

$$Y = L(P_A S_A + P_M S_M + P_S S_S) \qquad (1)$$

where:

Y = total output,

L = total labor inputs,

P_A, P_M, P_S = output per unit of labor input in agriculture, manufacturing and service sectors, respectively, and

S_A, S_M, S_S = share of total labor input from each sector.

The expression in the parentheses $(P_A S_A + P_M S_M + P_S S_S)$ then yields an average output per unit of labor for the aggregate economy. Multiplying this by the total labor inputs in the economy (L) yields total output (Y).

Average output per labor input can also be developed by substituting industry data for the sector data above. That is, (1) now becomes

$$Y = L(P_1 S_1 + P_2 S_2 + \ldots) \quad , \text{ or}$$

$$Y = L(\sum_i P_i S_i) \quad ,$$

1/ For a closer look at the historical evolution of economic concepts of technological progress and its role in economic growth, see Appendix A.

where now:

P_i = output per unit of labor input in the ith industry, and

S_i = share of total labor input from the ith industry.

Over time, total product (Y) could be increased by an increase in labor inputs (L), by an increase in product per labor input in the various industries (P_i), and by a reallocation of labor inputs from industries with low output per labor input to industries with high output per labor input (i.e., changes in the relative S_i's).1/

Use of labor inputs as a starting point has a strong base in economic tradition.

Looking back over most of the course of human history, until the Nineteenth Century, the one fundamental or nucleus source of general economic growth had been an expansion of total output. Expansion of total output, in turn, had been largely a result of increases in labor inputs--that is, increases in size of labor force--contributed by such forces as population growth, immigration, slavery or captivity, and so on.2/ Yet there had been little significant gain in income per capita.3/ Human society was larger and materially richer in the aggregate, but not appreciably better off in terms of the economic well-being of its members.

This is not to say that there had been no rise in welfare. Except for such setbacks and upheavals as followed the collapse of the Persian, Grecian, and Roman cultures, each age had been generally somewhat better off than its predecessors. In qualitative terms, historians concede that the life of the fuedal serf was in many respects a cut above that of his ancestors, just as the peasant and common man of Eighteenth Century Europe and America enjoyed a quality of life, if not culture, above that of Rome.

1/ Alternatively, we could view output as the sum of the various inputs (land, labor, capital) weighed by their respective marginal products. However, this suggested approach has the advantage of being more directly expressed in terms of per capita welfare by virtue of examining output per labor unit.

2/ For example, Edward Denison, The Sources of Economic Growth in the United States (New York: Committee for Economic Development, 1962), for an evaluation of the labor input variable in the Twentieth Century. For Nineteenth Century evidence see Gallman, "Commodity Output in the United States 1839-1899," Trends in the American Economy (New York: National Bureau of Economic Research, 1960); and P. David, "The Growth of Real Product in the U.S. Before 1840," Journal of Economic History, 27 (June 1967).

3/ See Simon Kuznets, ed., Income and Wealth of the U.S., Trends and Structures (Cambridge, England: Bowes and Bowes, 1952), pp. 221-41.

But in economic terms, real economic growth--gain in welfare, as measured by per capita income--had been relatively small, and ponderously slow.

Capital. With the emergence of political and social changes in the Nineteenth Century and growing industrialization, a second stimulus to output began to be felt, and at an accelerating pace. That stimulus was capital.

The role of capital in economic growth is too well known and widely documented in the literature of social policy and economic thought to require elaboration here. Perhaps a simple summation will suffice:

* First, addition of capital to labor serves not only to increase total output, but also to increase output per capita. (More input yields more output, plus the effect on productivity of labor.)

* Second, substitution of capital for labor may and usually does increase total output (which is why it is done), and almost always increases output per capita. (Tendency toward maximization of labor productivity.)

* When capital increases faster than labor inputs, the magnified effects of simultaneous but disproportionate increases in capital and labor can be dramatic. . . at least up to a point.1/ It is not difficult to understand, then, why much of economic theory from Adam Smith to John Maynard Keynes emphasized capital accumulation as a primary explanation of economic growth.2/

Technology. By the Twentieth Century, still another force had begun to find increasing recognition--that of technology and technological growth.

Per capita income had clearly been rising. . . and at a rate no longer explainable simply by increases in labor input (work force and employment)3/ or by growth of capital alone. In fact, the historical role

1/ The latter concept--that of capital actually outrunning labor--is largely one of recent origins, which has arisen from post-World War II experience with mass infusions of capital into underdeveloped nations. But since the issue turns about as much on the ability of a culture to assimilate unfamiliar technology as on its ability to assimilate capital *per se*, the topic can be deferred at this point.

2/ This was especially true of the classical economists, and of early proposals designed to set backward countries on the road to development.

3/ Increases in labor force explain some 64 percent of the increase in output in the Nineteenth Century, but only 19 percent in the Twentieth Century. (Gallman, *op. cit.*, p. 34.)

of labor inputs, which we have described in a preceding section, had begun to decline in importance. . . and not just relative to capital, but relative to total output.1/ Instead, what seemed to be at work was the nature of capital, or of capital + labor combinations.

Over the years, many features have been identified within various industries as explaining or contributing to this sort of second-stage rise in capital-labor productivity. Among these have been such things as--better organization of firm operations, economies of scale, improvements in the health and education of workers, on the job experience, and reduced down time due to various physical and social factors.

In a general sense, these and other occurrences have been lumped together and called, collectively, "technological progress." But even in a narrower construction, the term "technological progress" has been widely accepted to mean some prolific change in the nature or quality of particular capital or productive processes.

What was happening, then, was that not only was the amount of capital increasing, but also it was a different, more powerful sort of capital. The differences represented a favorable change or "growth" in technology. Moreover, whether one viewed technological growth in its broader or its narrower connotations, it was clearly present, and was exerting a marked upward push on per capita income.

At this point, two illustrations of the broader versus narrower constructions of technological progress may be helpful.

Education. Education overall has been receiving increasing attention in recent years. Long neglected as a component or determinant of technological growth, education is now being heralded in that quarter, as well. Why? Because in the field of international economic development it is becoming painfully evident that both a generally educated populace and a technically educated workforce are necessary ingredients for the success

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1/ Under the early "labor input" conceptions of economic growth, if increases in labor input were to increase output per capita, then it was essential either that (a) the labor force participation rate (percent of total population gainfully employed) should increase, or that (b) given a static participation rate, the average number of hours worked should increase. But typically, as incomes rose, workers chose to work fewer hours. Also, aside from the effect of immigration, the age structure of the population did not change dramatically, and so the participation rate did not rise significantly. Instead, it began to decline markedly following the boom of trade unionism in the early decades of this century.

of new technology. Education--which can be thought of as an investment in human capital through improvement in the skill and intellectual capabilities of that human capital--is necessary in order to prepare workers for handling sophisticated machinery, for realizing the value of changing technology, and for adapting their abilities to new equipment. Formal education also provides a source of scientific personnel who devise further new equipment, and a means of improving the ability of the entrepreneurs and changemakers who decide when and how to use the new advances.

Education, then, may be viewed either as a component of technological growth itself (broad construction) or as an external stimulus to it (narrower construction). Either way, however, it is clearly a contributor to economic growth.1/ And, as in the case of the "chicken-and-egg" analogy, in this context it may be immaterial which came first, the education or the technology.

Also, another point here should not be confused as some writers have apparently done: Education may be either a part of or stimulus to technology, but it is <u>not a substitute for technology</u>. Education alone cannot cause economic growth, nor can it stand as a sufficient explanation for economic growth. Rather, the benefit of education, in the context of economic growth, lies in its interaction with technology.

<u>Economies of Scale</u>. The matter of economies of scale is a second source of sometime controversy. Many would maintain that what economists call economies of scale or economies of size could occur without any change in technology. Indeed, this is the classic model. Others point out that technology, too, may change without affecting scale. Either of these is easy to deal with separately. But what of the third situation where, because of some technological change in processes or materials, the scale of some manufacturing operation may be greatly increased? If output per worker is thereby increased, do we attribute the increase in product to technology or to economies of scale?

Here, again, the point may be moot:

* In its broader construction, technological and economic growth may include many instances in which a change in scale of economic production is an outgrowth, or a natural accompaniment, or even an essential corequisite of technological change.

* Conversely, in its narrower construction, technological change may be fully differentiable from economies of scale, with the latter either an external product of or stimulus to the technological change.

1/ The general effects of education--for example, on increasing labor mobility--have long been recognized as positive.

On balance, it seems likely that the technological change will come first, opening the way for fruitful advances in scale of plant which could not have been achieved under the earlier level of technology.

Synthesis. The point of all this, of course, is not that such forces as technological change, education, economies of scale, and the like are competing factors which must be judged and scored for their contributions to economic growth, but that they are complementary factors which reinforce each other in expanding and accelerating economic growth. The confusion and occasional controversy arise out of attempts to measure and separate precisely the effects of a particular variable on the growth of output. But this problem is by no means peculiar to technological change.

As we have seen, these several growth-related factors are or may be heavily interdependent, so that one can never ideally separate their respective influences. All that can be done is, first, to establish workable measures, based on assumptions derived from the body of contemporary economic theory, which serve to provide reasonable bases for assigning shares of output among the conventional factors of labor and capital. As a second step, the balance of output increases not traceable to mere increases in the quantity of labor and capital can then be assigned to intangible input factors such as education, technology, etc.--which, alternatively, can be lumped together under a broad construction of the term "technological change." In either event, this step requires further assumptions and empirical testing.

Often, then, technological change is simply lumped from the outset under the shorthand term "residual." And it is this residual which is used to measure the contribution of technological change to growth in output.

V. TECHNOLOGICAL PROGRESS DEFINED

The factor of technological change is a difficult concept to define, since it is often accompanied by nearly simultaneous change in education, allocation of labor, and scale of production. Further difficulties arise in trying to separate and measure its effects. Typically, then, technological change is viewed as all of these changes taken together, and measured as the "residual." Thus, while only imprecisely measured, technological change is shown to be THE pervasive growth element. As Kuznets asserts, "continuous technological progress and the underlying series of scientific advances are the necessary condition for the high rate of modern growth."1/

Prior to any measurement of economic impacts resulting from technological progress, it is necessary to develop a conceptual framework within which these measurements will be made. Possibly, the most critical element of this conceptualization process is the development of a meaningful and usable definition of technological progress.

The Technologist's Concept

The technologist--scientist, engineer, technician--normally views technological progress in a framework of techniques. He is concerned with progress in technologies surrounding how products are produced, designed, marketed, and the like. His scope of interest lies then primarily in the pragmatic aspects of processes used in the flow from raw materials through to final goods and possibly even the reformation and recycling of these goods after their useful lifetime.

Although economic impacts of these improvements in techniques are of interest to the technologist, his economic analysis is usually performed on an extremely micro level. Often these take the form of marginal cost-benefit analyses rather than the more global question of ultimate return on the investment when considering potential replications of an innovation within the economy.

In short, the technologist perceives technological progress as: (1) improvements in production processes, (2) use of new materials, (3) improved reliability and quality of final goods, (4) creation of new final goods not possible with a previous technology level, etc. All of these, in one form or another, are readily identified results of technological progress. They are often manifested in new patents, new achievements, and so on.

1/ Simon Kuznets, Six Lectures on Economic Growth (New York: Free Press, 1959), p. 29, and Economic Growth and Structure (New York: W. W. Norton and Company, 1965), p. 195.

The Economist's Concept

The economist is interested in the economic impacts of technological progress. Typically, then, he is not so much concerned with specific technological advancements but instead considers these advancements collectively as one of the factors in the process of generating economic output.

Since the economist is not concerned with identification of discrete technical innovations, his orientation is normally directed toward factors that cause these innovations of various forms--that is, in technological progress in its totality. Some of the factors normally included in the determinants of technological progress are: (1) education, (2) scale of operations, (3) quality improvements in capital and labor, (4) increase in knowledge, (5) learning by doing, and others. These in effect are the underlying stimulants to advances in the technology level rather than manifestations of technological progress. The degree to which any of the fundamental determinants contribute to increased economic output is the subject of a significant body of published research.

There appear to be at least three alternative ways of measuring technological progress. Briefly, they are:

1. To explicitly estimate the separate effects of the individual determinants of technological progress.

2. Determination of the overall or aggregate impact of technological progress and the subsequent disaggregation to the various determinants.

3. Estimation of the total impact due to technological progress with no subsequent attempts at disaggregation.

Because of the difficulties in estimation in the first approach, it has been the least attempted methodology. The bulk of the research is oriented towards the second and third approaches. Many researchers, after measuring the aggregate impact, do not continue with the subsequent disaggregation because they believe that conceptually it is not possible to treat each of the determinants on an independent basis. That is, many of the determinants are highly related in a cause-effect relationship and it is often difficult to clearly identify which is cause and which is effect. As shown later, with appropriate assumptions, disaggregation can be performed with estimates of comparable reliability to that of aggregate impact measures.

A more philosophical discussion of economic thought as it relates to technological progress is contained in Appendix A.

Technological Progress in This Research

Because of the multi-faceted approach being pursued in this overall research program, our focus in this aspect of the research will be on the economist's concept of technological progress. That is, we view technology as one of the factors of production, working in concert with labor and capital. Because of the inherent difficulty of directly estimating the technology level being utilized in production at any point in time, our estimation procedures will consist of:

1. computing the output that should have occurred--expected output--with known levels of utilized capital and labor, and

2. attributing the difference between observed and expected output to technology.

Implicitly, then, if this difference--the residual--grows through time, one is led to the inevitable conclusion that technological progress is the cause of some fraction of economic growth. Output due to technology can then be distributed to the determinants of technological progress.

VI. ECONOMIC IMPACT OF TECHNOLOGICAL PROGRESS

In order to quantitatively assess the role of technological progress in economic growth, it is necessary to utilize mathematical models describing the mechanics of how output occurs through the combined influence of all its causal factors. We use a production function consistent with our concept of technology's role in generating output as discussed in the previous chapter.

Assumptions

As is the case with most modeling efforts, certain assumptions must be made around which the model is constructed and later empirically exercised. We will state, when appropriate, both explicit and implicit assumptions as they are used.

In structuring the methodology to measure the aggregate impact of technological progress, four fundamental assumptions are made.

1. Technological progress accounts for all output not explained by increases in utilized labor and capital input. This assumption is consistent with the bulk of published research in the field. It implicitly states that output is created by the inputs of capital, labor, and technology. Then, if increases in output occur without comparable increases in utilized labor and capital, the growth in output must have occurred through an improved level of technology being used in the production process. It should be noted that we have introduced the word "used." The reason is simple--only technology being used, as opposed to being simply in existence, contributes to output.

2. Improvements in the quality of labor and capital should be measured as a component of technology. This is a particularly relevant assumption when measuring the impact of technology in its broadest construction--that is, in the concept of the economist who often perceives technology as simply another factor of production. We will later depart from this assumption when we attribute portions of the growth due to technology to the determinants of technological progress.

3. In the long run, the elasticity of substitution of capital for labor for the U.S. private non-farm economy is assumed to be equal to unity. This assumption is made to assist in the specification of the production function. Moreover, the bulk of research performed by others supports this assumption at the long-run macro-level of interest. For a more detailed discussion of the implications of this assumption, the reader is referred to Appendix A--particularly page A-11.

4. Technological progress acts in a multiplicative fashion rather than additive in augmenting labor and capital in the output-generating process. This assumption is also widely accepted in that the additive assumption leads to conceptually implausible results. Theoretically, it states that output could be generated by technology alone--a result of little intuitive appeal.

The Production Function

In light of the previously stated assumptions, a production function of the form

$$Q_t = f(K_t,\ L_t,\ A_t) \quad , \tag{1}$$

where

Q_t = output in time period t ,

K_t = capital utilized during time t ,

L_t = labor expended in time t , and

A_t = level of technology applied during time t ,

is appropriate.1/ If it is further assumed that technological progress is "neutral," that is, the marginal rates of substitution of capital for labor are not affected, Eq. (1) can be rewritten as

$$Q_t = A_t f(K_t, L_t) \quad . \tag{2}$$

Equation (2) is the fundamental equation used by Robert M. Solow2/ in his pioneering work in measuring the impact of technology on economic growth. Because of its conceptual appeal and widely accepted results, we have applied his methodology in our empirical work.

1/ See Appendix A for a detailed discussion of production theory and results obtained with alternate production function approaches.

2/ Robert M. Solow, "Technical Change and the Aggregate Production Function," The Review of Economics and Statistics, August 1957, as reprinted in M. G. Mueller, ed., Readings in Macroeconomics (New York: Holt, Rinehart and Winston, 1966).

Briefly, the methodology is as follows. By differentiating (2) totally with respect to time, the following equation results.

$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + w_k \frac{\dot{K}}{K} + w_\ell \frac{\dot{L}}{L} \tag{3}$$

where

w_k = relative share of capital in income,

w_ℓ = relative share of labor in income, and

the dots indicate time derivatives. Assuming that $w_k = 1 - w_\ell$, Eq. (3) can be rewritten as

$$\frac{\dot{q}}{q} = \frac{\dot{A}}{A} + w_k \frac{\dot{k}}{k} \quad , \tag{4}$$

where

$q = Q/L$ and

$k = K/L$.

To compute A_t , using (4), it is necessary to obtain series for:

1. output per man-hour,

2. utilized capital per man-hour, and

3. capital share of income.

We, as well as Solow, view the economic unit of interest to be the U.S. private non-farm sector. Using a collection of data sources, we continued the original computations done by Solow for the 1909-1949 time frame forward to cover the 1949-1968 period. Table 1 shows the results in tabular format. Figure 1 graphically illustrates the behavior of the applied technology level or index A_t for the 1909-1968 period. The data sources and methodology are more completely described in Appendix B.

TABLE 1

THE VALUES OF A_t

Year	A_t	Year	A_t
1909	1.000	1939	1.514
1910	0.983	1940	1.590
1911	1.021	1941	1.660
1912	1.023	1942	1.665
1913	1.064	1943	1.733
1914	1.071	1944	1.856
1915	1.041	1945	1.895
1916	1.076	1946	1.812
1917	1.065	1947	1.781
1918	1.142	1948	1.810
1919	1.157	1949	1.853
1920	1.069	1950	1.964
1921	1.146	1951	1.977
1922	1.183	1952	1.979
1923	1.196	1953	2.025
1924	1.215	1954	2.042
1925	1.254	1955	2.120
1926	1.241	1956	2.090
1927	1.235	1957	2.103
1928	1.226	1958	2.125
1929	1.251	1959	2.183
1930	1.197	1960	2.196
1931	1.226	1961	2.233
1932	1.198	1962	2.309
1933	1.211	1963	2.350
1934	1.298	1964	2.413
1935	1.349	1965	2.444
1936	1.429	1966	2.459
1937	1.415	1967	2.489
1938	1.445	1968	2.540

A_t

TECHNOLOGY LEVEL IN THE 1909-1968 TIME FRAME

(Illustrative only - not to scale)

Figure 1

A cursory examination of Figure 1 discloses several interesting facts:

1. In the long run, the level of applied technology has been on a steady climb. In fact, the annual compound growth rate of A_t is greater than 1.5 percent over the period.

2. Two major departures from the steady climb of A_t both occurred after the war years. One possible interpretation of these declines is that the technology used during the war years was not utilized after the war. This was, of course, occasioned by the dramatic influx of veterans into the workforce. National priorities called for a departure from the optimal use of available technology--in order to minimize unemployment.

3. A dramatic upward climb in A_t has occurred since about 1929. The reasons for this are manifold--and vary among time periods. For example, during the Thirties, capital expenditures were quite limited, unemployment was at an all-time high, and industry was forced to utilize all possible existing technology to create output with minimum levels of capital and labor. After the slump in progress following World War II, industry purchased increased productivity through improvements in the quality of capital. New, more efficient machinery employing latest technological advances continued the rapid rise in technology being applied in the private, non-farm sector.

Synthesizing observations made so far and the empirical results obtained, technology--viewed in broadest terms as simply one of the factors of production--has grown at a rate approaching that of output per man-hour.

So far, technology has been incorporated into the production function as merely a multiplier-- A_t --to the combined effects of capital and labor. In the next section we will develop an interpretation of A_t consistent with our conceptual definition and in addition develop a methodology that permits quantification of the impact of technological progress in absolute terms rather than index numbers. That is, we will convert the measure of technology's role in the output generating process to a measure of dollars instead of an index number.

Aggregate Economic Impact: Gains Due to Technology

Referring again to the general form of the production function used to describe the output generating process,

$$Q_t = A_t f(K_t, L_t) \ ,$$

it can be seen that A_t augments the combined output producing capabilities of capital and labor. If, at some time period i, we let $A_i = 1.0$ and using the input data for K_i and L_i (these would be the actual quantities employed), we determine $f(K_i, L_i)$ so that it must equal Q_i --the observed output in period i. In essence, we have forced the functional form of f to be such that it describes all of the output in period i. Implicitly then, the existing technology applied during period i is embodied in f and the combined levels of capital and labor inputs.

Conceptually, it is then possible to hold the technology embodied in f, K_i and L_i constant. If comparisons between Q_j and $f(K_j, L_j)$ are then made for any other year j (where K_j and L_j are assumed to reflect quantities of capital and labor of quality existing in period i), the difference between output and capital-labor productive capability must reflect technological change relative to year i. Reviewing Figure 1 and Table 1, it can be seen that A_{1909} was set equal to 1.0 and that A_t represents technological progress then relative to 1909.

Pursuing this line of reasoning to the next obvious step leads to a quantitive dollars and cents measure of the economic impact of technological progress.

If Q_t, for any year t, is divided by A_t a measure of output that would have occurred in the absence of any technological change is obtained. That is, since $Q_t = A_t f(K_t, L_t)$, dividing both sides by A_t yields

$$\frac{Q_t}{A_t} = Q_t' = f(K_t, L_t) \quad .$$

Since we have said that f embodies the technology being applied in a reference year, say, year i, and that measures of K_t and L_t reflect only quantity changes relative to i, Q_t' must reflect the output achievable without changes in technology for any level of K_t and L_t.

A direct measure of technology's contribution to output can then be obtained by differencing Q_t and Q_t', recalling that Q_t is an observed fact. We call this difference the "gains due to technology, G_t, in period t." Mathematically,

$$G_t = Q_t - Q_t' = Q_t \frac{(A_t - 1)}{(A_t)} \quad .$$

Table 2 and Figure 2 show the quantity of G_t relative to 1949 for 1949 through 1968--the period of primary interest in this research and the only period we will refer to from here on--in tabular and diagrammatic forms, respectively. It is noteworthy that we have now defined A_{1949} to be equal to 1.0 since this is the reference year.

TABLE 2

GAINS DUE TO TECHNOLOGICAL PROGRESS, G_t
(1949 Base Technology)
(1958 $ millions)

Year	$ Output	Output with 1949 Technology	G_t
1949	266,200	266,200	--
1950	294,900	278,208	16,692
1951	316,200	296,345	19,855
1952	324,200	303,558	20,642
1953	340,700	311,711	28,989
1954	335,000	303,993	31,007
1955	364,400	318,531	45,869
1956	371,400	329,255	42,145
1957	377,200	332,335	44,865
1958	370,900	323,365	47,535
1959	398,300	338,115	60,185
1960	407,600	343,966	63,634
1961	414,800	344,232	70,568
1962	444,600	356,822	87,778
1963	463,800	365,773	98,027
1964	491,200	377,266	113,934
1965	521,700	395,527	126,173
1966	552,300	416,202	136,098
1967	573,500	427,029	146,471
1968	604,200	440,700	163,500
Total	$ 8,233,100	$ 6,869,133	$ 1,363,967

Summarizing, Table 2 shows that technological progress--in its broadest definition--accounts for a significant portion of the total output during the 1949-1968 period. Output during the period increased from $226 billion, in 1958 constant dollars, to $604 billion. The total output for the period 1949-1968 was approximately $8 trillion. Had there been no increase in utilized technology, output for the period would have been $6.9 trillion. Therefore, technology has contributed $1.364 trillion (or about 16 percent) of the total output in the period. It is of interest that the lion's share of this occurred in the 1964-1968 period. About $686 billion of cumulative G_t occurred in these years.

OUTPUT AND GAINS RESULTING FROM TECHNOLOGICAL PROGRESS
(1949-1968)

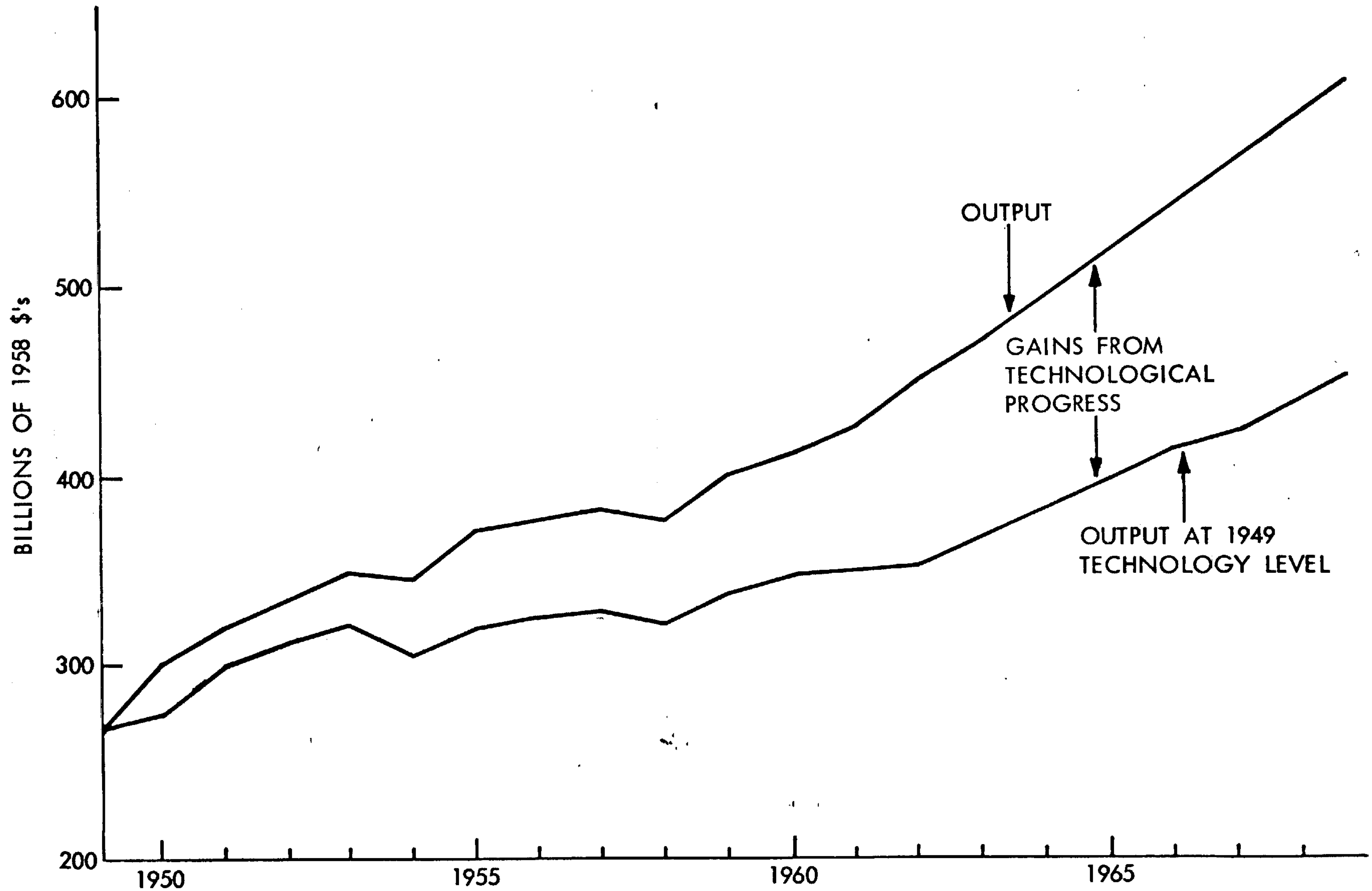

Figure 2

VII. DETERMINANTS OF G_t

As has been indicated previously, technological progress, when considered a factor of production, comes about because of the combined effects of a number of determinants. We refer to these factors as the determinants of technological progress and, as was demonstrated in the previous chapter, since G_t is generated by technological progress, the determinants can be considered in a "cause and effect" framework with respect to G_t. That is, the determinants of technological progress are also the determinants of G_t.

The goal here then is to assess the portions of G_t that can be attributed to its various determinants.

The Determinants of G_t

Consistent with our definition of technological progress, there are seven fundamental determinants of G_t :

1. Age mix of the work force.
2. Sex mix of the work force.
3. Educational level of the work force.
4. Health of the work force.
5. Work-week length.
6. Economies of scale.
7. Research and development.

The degree to which any of these contribute to G_t varies. As will be shown, this is particularly true in the 1949-1968 time frame where some long-run effects are not as evident. The remainder of this chapter will be concerned with the apportionment of G_t to the various determinants. The methodology will consist of successive assignments of portions of G_t to the determinants.

Our approach to the apportioning process is similar, in concept, to the method used by Denison in his monumental work of 1962.[1] In fact, we rely heavily on some of his assumptions in areas where little, if any, quantitative data exist.

1/ Denison, op. cit.

Age Mix of the Work Force. In analyzing the potential influence on economic output, as measured in terms of G_t, of improved productivity of the work force because of shifts in its age composition, it is first necessary to ascertain to what extent changes in the work force age distribution have occurred. Clearly, if little change in the age composition has occurred, then one could conclude that little change in productivity should result.

Data published by the Bureau of Labor Statistics indicate that there has been essentially no shift in the age distribution of the civilian labor force from 1949 through 1968. Table 3 below shows the percentages falling within the various age group cells.

TABLE 3

DISTRIBUTION OF CIVILIAN LABOR FORCE BY AGE GROUPS
(Percentage)

Age Group	1949	1958	1968
16-17	2.78	2.88	3.53
18-19	4.22	3.69	4.83
20-24	11.98	9.38	11.82
25-34	23.51	21.11	19.95
35-44	22.37	23.59	21.07
45-54	18.12	21.23	20.83
55-64	12.12	13.50	13.92
65 and over	4.90	4.62	4.00
Total	100.00	100.00	100.00

Source: Handbook of Labor Statistics, 1970, U.S. Department of Labor, Bureau of Labor Statistics (U.S. G.P.O.: Washington, D. C.).

Using the distribution percentage and the age cell midpoints, the average age of the labor force is calculated to be 39, 40.3 and 39.5 years for 1949, 1958, and 1968, respectively. We assume that, due to the negligible change in the average age of the labor force, there has been no change in labor productivity in the 1949-1968 period due to changes in age composition of the work force. Therefore, the contribution to G_t from age changes is zero.

Sex Mix of the Work Force. Similar to changes in the age composition of the work force, changes in the sex composition, that is, the ratio of males to females, could alter the productive capacity of the labor force.

As might be suspected, there has been a continual change in the work force sex mix during the Twentieth Century. In fact, this shift has been significant even within the 1949-1968 time frame. Table 4 shows the distributions in 1949, 1958, and 1968 for the non-agricultural, private, employed labor force as taken from BLS data. As the data show, the percentage of females has risen from approximately 31 percent in 1949 to 38 percent in 1968.

TABLE 4

PRIVATE NON-AGRICULTURAL LABOR FORCE SEX MIX

	1949		1958		1968	
	Thousands	%	Thousands	%	Thousands	%
Male	34,584	69.18	37,827	65.84	44,957	62.35
Female	15,409	30.82	19,623	34.16	27,147	37.65
Total	49,993	100.00	57,450	100.00	72,103	100.00

Source: Handbook of Labor Statistics, 1970, U.S. Department of Labor, Bureau of Labor Statistics (U.S. G.P.O.: Washington, D. C.).

Clarence Long1/ has constructed a series for "adult-male equivalents" participating in the employed labor force for the decennial years of 1890-1950. This series gives an adult female worker a weight that rises gradually from 52 percent of that of an adult male in 1889 to 67 percent in 1949. The intervening years are weighted as shown below:

Year	Adult Male Equivalent Weight
1889	52 percent
1909	54 "
1929	57 "
1939	58 "
1949	67 "

1/ Clarence Long, The Labor Force Under Changing Income and Employment (National Bureau of Economic Research, 1958).

If it is assumed, as it was by Denison, that the growth in the weighting factor in the 1929-1949 period will continue, it is possible to compute--by linear extrapolation--the weights for 1958 and 1968. These are calculated as 71.5 percent and 76.5 percent, respectively. Utilizing the weighting factors, it is then possible to calculate the equivalent adult-male labor force for each of the three years. In addition, the ratio of equivalent adult males to total labor force can be calculated. This ratio represents a measure of the productive intensity of the labor force in that it simultaneously accounts for the relative decline in the percentage of males and the increase of females as well as their productive capacity. Letting the ratio equal 100 for 1949 permits the construction of an index number reflecting improved labor quality changes due to sex mix changes. Table 5 shows index values as well as base data for the computations.

TABLE 5

LABOR QUALITY CHANGES DUE TO SEX MIX CHANGES

	1949	1958	1968
1. Total Work Force (thousands)	49,993	57,450	72,103
2. Males in Work Force (thousands)	34,584	37,827	44,957
3. Females in Work Force (thousands)	15,409	19,623	27,147
4. Female Weighting Factor	0.67	0.715	0.765
5. Female "Adult Male Equivalents"	10,324	14,030	20,767
6. "Adult Male Equivalents" (2 + 5)	44,908	51,857	65,724
7. Fraction of "AME" of Total	0.898	0.903	0.912
8. Index of Labor Quality Change	100.0	100.6	101.6

As Table 5 indicates, the index of labor quality change due to changes in the sex mix and improved productivity of the female portion of the work force has grown from 100.0 to 101.6 or an increase of 1.6 percent over the 19-year period. This reflects an average annual growth of 0.08 percent.

Making the assumption that the index of labor quality changes due to sex mix changes can be interpreted as a multiplier (after dividing by 100) to labor inputs of 1949 quality level, it is possible to recalculate A_t and G_t reflecting quality changes in the labor force. These calculations yield contributions to G_t from sex mix changes shown in Table 6 and described in Appendix C.

TABLE 6

SEX MIX CHANGES

Year	G_t Due to Sex Mix Changes (1958 $ millions)
1949	0
1950	323
1951	242
1952	530
1953	1,047
1954	1,191
1955	1,570
1956	1,845
1957	2,098
1958	2,072
1959	2,379
1960	2,857
1961	3,178
1962	3,531
1963	3,565
1964	4,210
1965	4,780
1966	5,337
1967	6,099
1968	6,732
Total	53,586

The annual series of gains due to sex mix changes in the labor force reflects the portion of the original G_t attributed to this determinant of technological progress. The remaining determinants will account for the balance of G_t. Specifically, the original total gains due to all determinants has been reduced by 3.93 percent to $1.310 trillion from $1.364 trillion in the 1949-1968 time period. It should be noted that although the quality index grew only 1.6 percent in the period, the annual series in Table 6 reflects the multiple effects of increased quantities as well as quality.

Education of the Work Force. It is widely recognized that probably one of the most important determinants of technological progress is increased education of the work force. Undisputed are the relatively higher earnings of that segment of the work force with high school, college and graduate level educations over those in the work force of elementary

school, or less, educational attainments. Higher earnings, of course, generate correspondingly higher contributions to the output of the private economy. Denison devotes significant attention to this determinant of technological progress in his study. In fact, he attributes approximately one-third of the growth in output during 1929-1957 to increases in education.

Denison's index of the quality change in labor is constructed through the use of various data sources and assumptions. Generally, the approach is as follows:

1. He assumes three-fifths of the average income differentials between groups with different educational attainments to be a result of improved education. His 40 percent discounting is designed to reflect, among other things, a potential correlation between basic intelligence and educational level, greater energy, higher motivation and application that would contribute to a possibly higher earnings potential without additional education for these groups.

2. Based on data available for males 25 years or older, Denison calculated what the average earnings would have been if the earnings at each educational level were a constant fraction of actual 1949 earnings of eighth grade graduates. He states that, "The differences from period to period in average earnings can be used to isolate the effect of changes in the length of schooling, measured in years, on average income."

3. Adjusting the above index for the increased days in school per school year attended for each age group (reflecting when they attended school) yields the full contribution of the increase in the amount of education to labor output per worker.

4. All of these influences can then be interpreted simultaneously in the form of an index number that would represent the relative quality changes in the labor force due to improved education.

Using Denison's original series for the index of labor quality changes due to education but converting the series to measure changes relative to 1949 (that is, we let the index equal 100 for 1949), we have constructed a series that reflects the effect of education on labor productivity. Table 7 contains this index series. Our interpretation of this index is that, for example, the productivity (output per man-hour) of the work force in 1968 is 19.7 percent higher than the work force in 1949 due to improved education, everything else remaining constant.

Table 8 summarizes that portion of gains due to technological progress attributed to the two significant determinants--sex mix and educational level of the labor force--discussed thus far. Appendix C presents the detailed computations.

TABLE 7

INDEX OF LABOR QUALITY AS AFFECTED BY EDUCATION

Year	Index	Year	Index
1949	100.0	1959	110.3
1950	101.0	1960	111.4
1951	102.0	1961	112.4
1952	103.0	1962	113.4
1953	104.0	1963	114.5
1954	105.0	1964	115.5
1955	106.1	1965	116.5
1956	107.1	1966	117.6
1957	108.2	1967	118.7
1958	109.2	1968	119.7

TABLE 8

G_t DUE TO SEX MIX AND EDUCATION CHANGES

Year	G_t Due to Sex Mix and Education ($millions)
1949	0
1950	1,990
1951	4,000
1952	6,453
1953	9,211
1954	11,307
1955	14,416
1956	18,945
1957	20,498
1958	22,205
1959	25,885
1960	29,400
1961	32,086
1962	35,806
1963	39,317
1964	43,581
1965	48,696
1966	54,670
1967	59,875
1968	65,178
Total	543,519

The combined effects of quality changes in the labor force discussed so far account for 39.8 percent of the original cumulative G_t attributed to technological progress. Education itself accounts for a 35.9 percent reduction in G_t. In absolute terms, sex mix changes, age mix changes and education account for $543 billion in the increase in output during the 1949-1968 period. This represents approximately 6.7 percent of the total output in the period. The other determinants of technological progress account for the remaining $820 billion of the original cumulative G_t or approximately 10 percent of total output in the period. We will investigate the apportionment of this balance to the other determinants in succeeding sections of this chapter.

Health of the Labor Force. We, as have others, recognize that because the general health of the labor force has been on a continual upswing, productivity of the labor force must have been affected. This, of course, would be particularly true over the long run, say, 1900 to present. The degree to which this change in productivity due to health would be observable in a period of relatively short duration, as is the period 1949-1968, is questionable.

Markley Roberts[1/] (as quoted by Denison) states that "improving health has been an important factor in the advance of American productivity, and continuing improvement of health standards will contribute to further economic growth." As Denison points out, however, Roberts neither quantified this judgment nor provided supporting evidence.

We will assume that improvements in labor quality due to improved health are not significant in the 1949-1968 time frame. Our rationale for this assumption is as follows:

1. Given the relatively high levels of health in the United States, increases over a 20-year span are probably fractional.

2. These increases in productivity have probably been offset by increasing sick-leave benefits which are freely taken advantage of by the labor force.

It is therefore implied that health improvement has not been a significant determinant of technological progress and therefore has not measurably contributed to generation of G_t during the 1949-1968 period. Considerable research is required to quantitatively support this contention. We do not feel that our results will be sensitive to the outcome of such research in that the quantitative results should support our original assumption.

1/ Denison, op. cit., p. 51.

Shorter Work-Week Length. In the period of interest, the average weekly hours of production of nonsupervisory workers on private non-agricultural payrolls was reduced from 39.4 in 1949 to 37.8 in 1968.1/ This represents a change of 4 percent over the period or 0.214 percent per year.

We assume that this negligible change in hours has had no effect on labor productivity--in terms of productivity per man-hour--over the period. This then implies that shorter hours have not contributed to G_t in our period of interest.

Economies of Scale. Of the determinants of technological progress, the most widely studied is probably economies of scale. The close relationship between technological innovation and economies of scale is often viewed in a circular cause-effect system. That is, it is difficult, in many isolated specific examples to clearly identify which is cause and which is effect--technology or economy of scale. Should the development of a new automated production process capable of high production volumes at lower cost be credited with the increased market penetration possible due to lower cost or should scale economies take the credit? Clearly, one cannot answer the question without a degree of subjective judgment.

Since scale is represented by size and if it is assumed that the number of employees per establishment is an acceptable surrogate for size, estimates of scale changes can be obtained. Data published in the 1967 Census of Manufactures have been used to obtain insights into scale changes over the 1949-1968 period. Table 9 gives the distribution of establishment sizes for the Census years.

TABLE 9

PERCENT OF TOTAL MANUFACTURING BY ESTABLISHMENT EMPLOYMENT

	Percent Establishments by Average Employees									
Year	1-4	5-9	10-19	20-49	50-99	100-249	250-499	500-999	1,000-2,499	2,500+
1947	29.2	19.4	16.9	16.6	7.8	5.9	2.3	1.1	0.6	0.2
1954	37.3	16.5	14.6	14.9	7.4	5.5	2.1	1.0	0.5	0.2
1958	35.4	17.0	15.7	15.5	7.3	5.4	2.1	0.9	0.5	0.2
1963	36.5	15.8	15.3	15.4	7.5	5.7	2.2	1.0	0.4	0.2
1967	38.4	12.9	13.6	16.0	8.2	6.5	2.5	1.1	0.5	0.2

1/ Handbook of Labor Statistics, 1969, U.S. Department of Labor, Washington, D.C., July 1969, p. 128.

An analysis of Table 9 indicates that there has been essentially no change in the percentage of firms with 100 or more employees in the 1947-1967 period. In fact, there has been a slight, but discernible, shift from the 5-to-20 employee range to the 1-to-4 range during the period.

All of this then indicates that there has been no significant upward establishment size shift in the 1947-1968 period. We assume this to be true for the 1949-1968 period as well.

Since no significant scale changes occurred in manufacturing, we assume that improved economies of scale in manufacturing have been minimal. A similar analysis in the selected services segment of the service sector disclosed that there has been no significant scale change there as well. In fact, establishments with 20 or more employees were 2.6 percent of all establishments in both 1954 and 1963. We assume, then, that economies of scale have not contributed significantly to G_t in the 19-year period of interest within the private nonfarm sector.

Research and Development. The remaining determinant, R&D, accounts for the balance of G_t . It is not surprising that the lion's share of the original G_t should be attributed to this determinant. Of all the determinants earlier cited and subsequently discussed, R&D is possibly the only determinant which is specifically funded to increase the existing technology.

At the firm level, R&D activities are conducted to:

* Improve production process
* Develop new consumption products
* Improve existing products
* Reduce marketing, administrative and distribution cost of consumption goods.

Moreover, these are merely a sampling of broad categories of R&D orientation within industry. All of these activities are performed with specific objectives in mind, however. This objective is improved, or at worst continued, economic viability of the firm.

At a macro level, such as public sector research in health, transportation, space, etc., the objectives vary. In an economic sense, however, the result of all of these activities is increased economic output and productivity.

Up to this point we have examined all determinants of G_t on our list except R&D. In total the determinants other than R&D were found to account for approximately 40 percent of the economic gains due to

technological progress during the 1949-1968 period. We presume that R&D is the determining force behind the balance. Since R&D is the one determinant specifically focused on the generation of new knowledge, problem solving, and new or improved processes and products, it is no surprise that the bulk of G_t --60 percent--is attributable to the nation's R&D activities.

Table 10 indicates the shares of G_t attributable to the three significant determinants: R&D, education, and sex mix during the period under study. The other four determinants of economic gains from technological progress, age mix, work-week length and health, were found to have negligible impacts during the 1949-1968 time frame.

TABLE 10

GAINS (G_t) DUE TO THE DETERMINANTS OF TECHNOLOGICAL PROGRESS

(1958 Million $)

Year	Sex Mix Changes	Education	R&D	Total
1949	0	0	0	0
1950	323	1,667	14,702	16,692
1951	242	3,758	15,855	19,855
1952	530	5,923	14,189	20,642
1953	1,047	8,164	19,778	28,989
1954	1,191	10,116	19,700	31,007
1955	1,570	12,846	31,453	45,869
1956	1,845	17,100	23,200	42,145
1957	2,098	18,400	24,367	44,865
1958	2,072	20,133	25,330	47,535
1959	2,379	23,506	34,300	60,185
1960	2,857	26,543	34,234	63,634
1961	3,178	28,908	38,482	70,568
1962	3,531	32,275	51,972	87,778
1963	3,565	35,752	58,710	98,027
1964	4,210	39,371	70,353	113,934
1965	4,780	43,916	77,477	126,173
1966	5,337	49,333	81,428	136,098
1967	6,099	53,776	86,596	146,471
1968	6,732	58,446	98,322	163,500
Total	53,586	489,933	820,448	1,363,967
% of Total G_t	3.9	35.9	60.2	100.0

Figure 3 summarizes the study findings with respect to economic gains attributable to technological progress over the 1949-1968 time period. Additional quantities of labor and capital supplied 57 percent of the growth in the private nonfarm economy during the period. Technological progress accounted for the rest or 43 percent with R&D the prime determinant for 26 percent and 17 percent attributable to all other technological progress determinants. As a result of these trends, technology brought into productive application since 1949 was accounting for about 37 percent of output by 1968. This translates into significant increases in labor and capital productivity through technological progress.

OUTPUT AND G_t DETERMINANTS
(1949-1968)

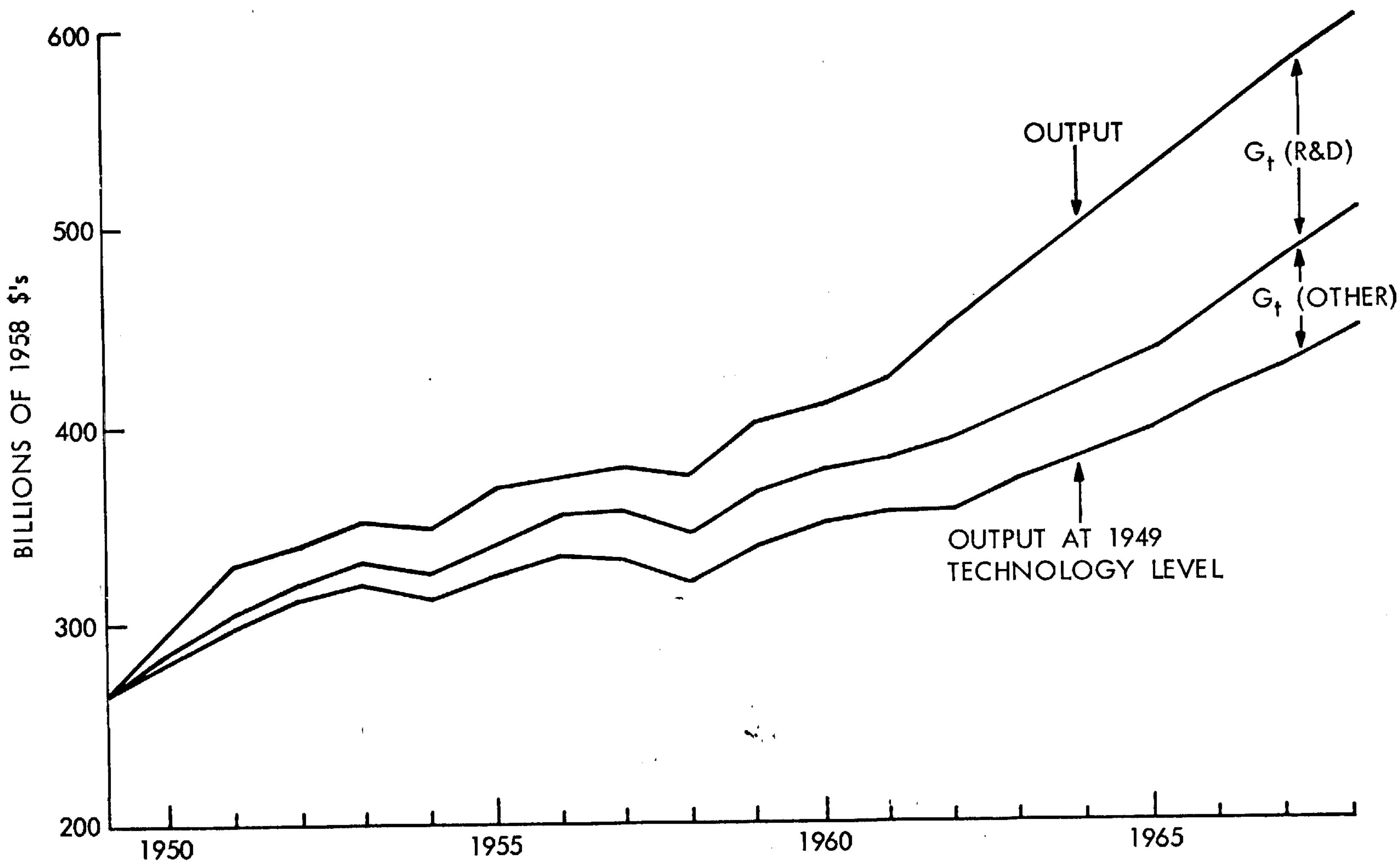

Figure 3

VIII. GAINS DUE TO RESEARCH AND DEVELOPMENT

As was demonstrated in the previous chapter, R&D is the predominant determinant of technological progress. In fact, during the period 1949-1968, R&D generated $820 billion of additional output. This represents approximately 10 percent of the total output of the economy in the same period. In this chapter, we will develop the rationale for and empirical parameter estimates of a model describing the R&D output generating process. Our inquiry into quantitative relationships between R&D and its associated gains in output, which we denote G(R&D) , will permit assessment of economic returns from R&D investments.

Time Lag Relationships

It is generally agreed that there is a definite time lag between R&D activity and when those activities contribute to economic returns--if returns, in fact, occur. At the micro level, where one can deal with discrete, identifiable technical innovations--a new product, process, etc.--and the subsequent generation of economic impacts--increased sales, reduced costs, etc.--it is possible to fairly precisely estimate this time lag relationship. On the other hand, for macro economic systems such as the private nonfarm U.S. economy, the time lag relationships become extremely difficult to determine.

There are two major reasons for this difficulty:

1. It is practically impossible to identify the numerous technological innovations resulting from the widely dispersed R&D activities being conducted within the system. The complexity of the process is illustrated in Part II of the report.

2. It is equally as difficult to identify and quantify the economic impacts of these unidentifiable innovations.

These difficulties can be overcome by utilizing two surrogate measures for the cause and effect measures.

First, we assume that R&D--by design--creates a continuous flow of technological innovations and that the measure of the "quantity" of these innovations is proportional to the amount of the R&D performance during some time period. It should be noted that our measure of "quantity" is not necessarily an absolute measure, such as the number of patents issued, but rather, the collective ability of these innovations to impact economic output by creating G(R&D) .

Second, as we allude to above, our measure of the economic impact of R&D activity is the generation of gains in economic output unexplained by the classical factor inputs of capital and labor and the other determinants of technological progress. Specifically, our measure of the long-run return from R&D is the G(R&D) stream generated by an expenditure for R&D in some time period. These effects would, of course, be in addition to the immediate multiplier types of output generated by the R&D expenditure in the period in which the expenditure is made.

Returning to the question of the time-lag relationships between R&D expenditures (performance) and the subsequent generation of G(R&D), there are basically two lag distributions of interest. First, there is the lag between R&D occurrence and when net contributions to output begin to be positive--that is, the period required to return the investment and create the initial G(R&D). Second, once positive net contributions appear, there is a finite life to the stream of G(R&D) created by an R&D activity. We explore each of these time relationships as well as their joint effect in the following discussion.

Initial G(R&D) Lags. Quantification of this widely recognized and discussed phenomenon has, to date, been less than satisfactory. Even in very specific instances of technological innovations, the precision with which the exact dates of innovation and subsequent return of investments can be determined is suspect. Too often, innovations occur as a result of efforts spread over many years. Recognizing when "the" innovation occurred must, at best, be considered a judgmental decision. Schmookler,1/ in his study of patents and their economic impact, attempts to quantify these relationships--and has some success. Unfortunately, his orientation focuses on time lags between patents and subsequent marketable consumption goods.

Mansfield2/ traces the introduction of diesel locomotive power within American railroads. His analysis suggests that significant lags existed--on the order of 20 years--before the majority of U.S. railroads decided to dieselize completely.

1/ Jacob Schmookler, Invention and Economic Growth (Cambridge, Mass.: Harvard University Press, 1966).

2/ Edwin Mansfield, The Economics of Technological Change (New York: W. W. Norton & Company, 1968).

In both of these analyses, the time lags were found to be significant. The focus was, however, on major dramatic innovations and the time lags are, therefore, understandably long. Few radical changes are implemented in a short time period. As we have pointed out previously, innovations, when viewing a macro economic system, are many and cover a broad spectrum of complexity. Some are insignificant when viewed next to diesel power, computers, jet engines and the like. These minor innovations do nevertheless generate economic return, if implemented. We assume an innovation not implemented to be one not worthy (in the eyes of the decision-maker) of application and therefore it would not even return its investment. At the macro level the "losers" are averaged with the "winners." As we will show, the average indicates more winners than losers.

Since innovations span a broad spectrum in terms of technical significance or complexity (from atomic power plants to the "Hula-Hoop"), it seems reasonable that the rate at which these innovations are implemented varies as well. From a purely pragmatic standpoint, it is conceivable that some innovations can be conceived, developed, implemented, return their original investment, generate positive contributions to G(R&D) and disappear all within the same calendar year. The "Hula-Hoop" is a notable example, and there are possibly thousands of others.

More complex innovations may take a considerable period before the investment is returned. For example, in the case of electronic consumer goods; significant product, process and marketing development efforts are required subsequent to initial product conception. Some of these activities will be time-consuming as well as requiring additional investment. This would then lengthen the time lag between innovation and return of investment--although only the R&D investment is of concern here.

Because of the sparsity of empirical data on time lags between innovation and return of investment and the inherent difficulties in developing these lag distributions at the macro level, we have approached the problem of obtaining this distribution by another means. Best estimates, most likely, come from individuals involved in R&D management on a continuing basis. These would be U.S. corporations which engage in R&D activities to ensure continued economic viability and market shares in a competitive environment. Estimates by responsible individuals from a cross-section of industry should yield a highly credible quantitative lag distribution. However, few of these data are available. There is one notable exception--the McGraw-Hill survey, "Business' Plans for New Plants and Equipment."

McGraw-Hill Survey. The McGraw-Hill Department of Economics has been conducting surveys of planned expenditures for research and development performed by business since 1956. Table 11 indicates the percent of total employment accounted for in the 1956 survey. As stated by Greenwald

(Table 11 source), "Our sample does include almost every large company in United States industrial and commercial fields." The 1968 Survey included some 900 companies accounting for an estimated 80 percent of all U.S. R&D performance and distributed by industries essentially as the 1956 data indicate.

TABLE 11

PERCENT OF TOTAL EMPLOYMENT ACCOUNTED FOR IN MCGRAW-HILL SURVEY, BY INDUSTRY, 1956[a]

Industry	Percent of Total Employment Accounted for by Survey Respondents
Primary metals	68
Machinery	44
Electrical equipment	66
Aircraft and parts	53
Fabricated metals and ordnance	33
Professional and scientific instruments	21
Chemicals	73
Paper	31
Rubber	63
Stone, clay, and glass	30
Petroleum	83
Food	33
Textiles and apparel	10
Other manufacturing	29
Total manufacturing	38
Nonmanufacturing	21
All industries	30

a/ Based on the ratio of employment in the McGraw-Hill sample of companies relative to total employment in each industry according to the data from the survey conducted for the National Science Foundation by the Bureau of Labor Statistics, U.S. Department of Labor.

Source: Greenwald, Douglas, "The Annual McGraw-Hill Research and Development Survey," Methodology of Statistics on Research and Development (NSF 59-36; June, 1959).

One of the questions in the R&D portion of the survey is, "How soon do you expect your expenditures on research and development to pay off?" The 1968 responses to this question are tabulated below:

	Percent of Companies Responding
2 years or less	19
5 years or less	90
9 years or less	96
10 years or more	4

Since the federal government supplies industry with over half the funds for R&D performed for industry, it is worth noting that the pay-back expectations must reflect a mix of time estimates for both government and private projects.

Because the data were grouped in intervals, we have approximated the distribution of responses by a Poisson distribution with a mean of three years. The probability, P_i, that payoff occurs i years after the R&D activity occurs is shown in Table 12 for <u>each</u> year-lag.

TABLE 12

LAG DISTRIBUTION

Years Lag After R&D (i)	Probability that Payoff Occurs in Year i (P_i)
0	0.05
1	0.15
2	0.22
3	0.22
4	0.17
5	0.10
6	0.05
7	0.02

Assuming that "payoff" means "return of investment," the lag distribution above gives the probability that net positive contributions to G(R&D) begin for each year after the R&D activity. The distribution shows that G(R&D) is least likely to occur soon or long after R&D. The most likely years for initial G(R&D) are in the two to four year lag periods.

Once R&D has recovered its investment and begins to generate a stream of G(R&D), positive contributions to output over those expected as a result of labor and capital inputs continue. They do not, however, continue ad infinitum. The following section explores the lifetime characteristics of G(R&D).

Lifetime Distribution. Having developed a distribution of lag between R&D and initial G(R&D), it is necessary to describe the length of time that contributions to G(R&D) are expected to occur. Research in this aspect of the process is essentially non-existent. There does, however, exist a quantitative basis for the development of a lifetime distribution based on research performed by Stanford Research Institute (SRI) as special studies in its Long Range Planning Service.

In two studies performed by SRI in 1965, characteristics of growth products 1/ and timing of "top-out" in growth products 2/ were analyzed. The first of these studies indicated that of the products with high growth rates (greater than 6 percent per annum) during the 1957-1962 period, 84 percent of consumer goods had at least average technological and engineering requirements. Of the nonconsumer growth products, 12 percent had high technological and engineering requirements and 86 percent had average requirements. That is, no less than 98 percent of the nonconsumer growth products studied had at least average technological and engineering requirements. Because of the high technological requirements, it can be assumed that high R&D requirements existed for these products as well.

In "Top-Out in Growth Products," research done by SRI indicated that, on the average, sales in these products stopped growing (topped-out) approximately four years after introduction. Company responses to a survey indicated that 52 percent of the companies reduced prices--and, thereby, economic output and gains in output as previously described--after top-out occurred. In addition, 57 percent of the companies indicated that they changed the variety of the product line--usually additions--to off-set the decline in sales of growth products. The most often pursued course of action to counteract top-out was to improve the quality of the product.

1/ Douglas A. Hurd, "Characteristics of Growth Products," Long Range Planning Service (Menlo Park, California: Stanford Research Institute, 1965).

2/ John A. Butler, "Top-Out in Growth Products," Long Range Planning Service (Menlo Park, California: Stanford Research Institute, 1965).

In effect, counter-measures to top-out were to:

- reduce prices,
- create new products,
- improve the old product,

the last two of these requiring technological inputs.

It is assumed that high growth rate products result from the development and application of technological knowledge which in turn is increased through R&D activity. Moreover, it is assumed that the time to top-out of growth products typifies the average life of the G(R&D) stream created by R&D results. Recognizing that not all life-times will be exactly four years, it is assumed that a Poisson distribution with a mean of four years will describe the probability of the lifetimes other than four years in length of G(R&D) streams. Figure 4 illustrates the distribution.

The distribution indicates that there is a small probability that the lifetime will be zero to one year as well as eight or more years. In addition, the lifetime will be less than seven years with a probability of approximately 0.9. Table 13 is a tabular presentation of the individual yearly probabilities for the lifetime distribution.

TABLE 13

G(R&D) LIFETIME DISTRIBUTION

Years of G(R&D) Lifetime	Lifetime Probability
0	0.0183
1	0.0733
2	0.1465
3	0.1954
4	0.1954
5	0.1563
6	0.1042
7	0.0595
8	0.0298
9	0.0132
10	0.0053
11	0.0019

G(R&D) LIFETIME DISTRIBUTION

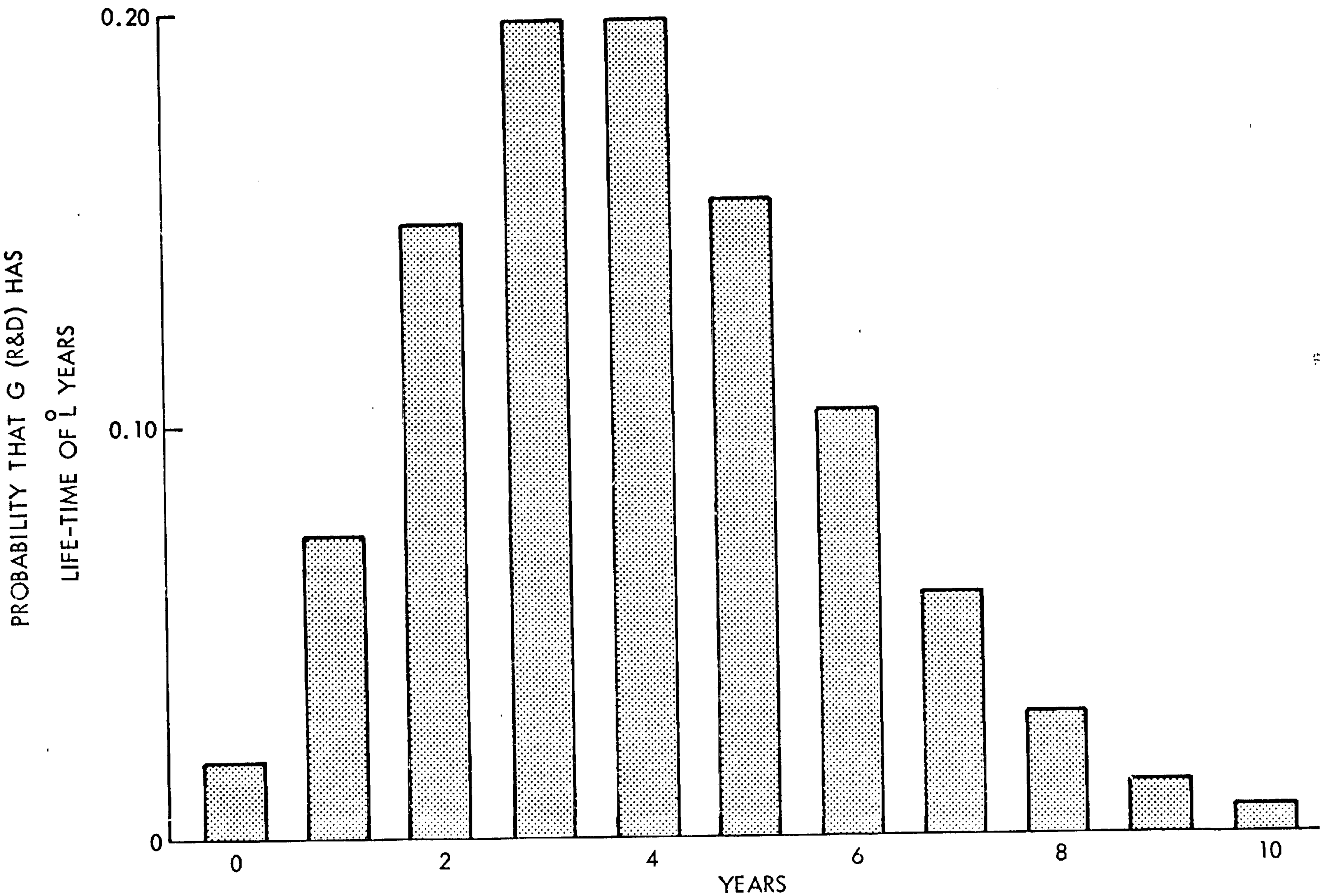

Figure 4

G(R&D) Generation Pattern. With the lag and lifetime distributions developed, the combined effect of these distributions can be utilized to describe the stream of contributions to G(R&D). The process of combining these two time relationships will reflect that there is a finite probability associated with the starting time of G(R&D) as well as the probabilistic characteristics of the life of the G(R&D) stream. In statistical terminology, the joint distribution will be a convolution of the lag and lifetime distributions. Appendix D describes the mathematical procedure for the convolution process.

Figure 5 is a graphical representation of the distribution obtained by convoluting the lag and lifetime distributions. The height of each bar represents the probability that R&D activity will be contributing to G(R&D) in the corresponding years after the R&D activity occurs. The distribution peaks at six and seven years and is essentially zero after 14 years. The total time span considered is 18 years in addition to the current year. Table 14 presents the distribution in tabular form.

TABLE 14

G(R&D) GENERATION PATTERN

Year Lag	Weight
0	0.000911
1	0.006384
2	0.022346
3	0.052136
4	0.091233
5	0.127721
6	0.149003
7	0.148995
8	0.130216
9	0.100746
10	0.069569
11	0.043116
12	0.024060
13	0.012084
14	0.005434
15	0.002162
16	0.000744
17	0.000210
18	0.000041

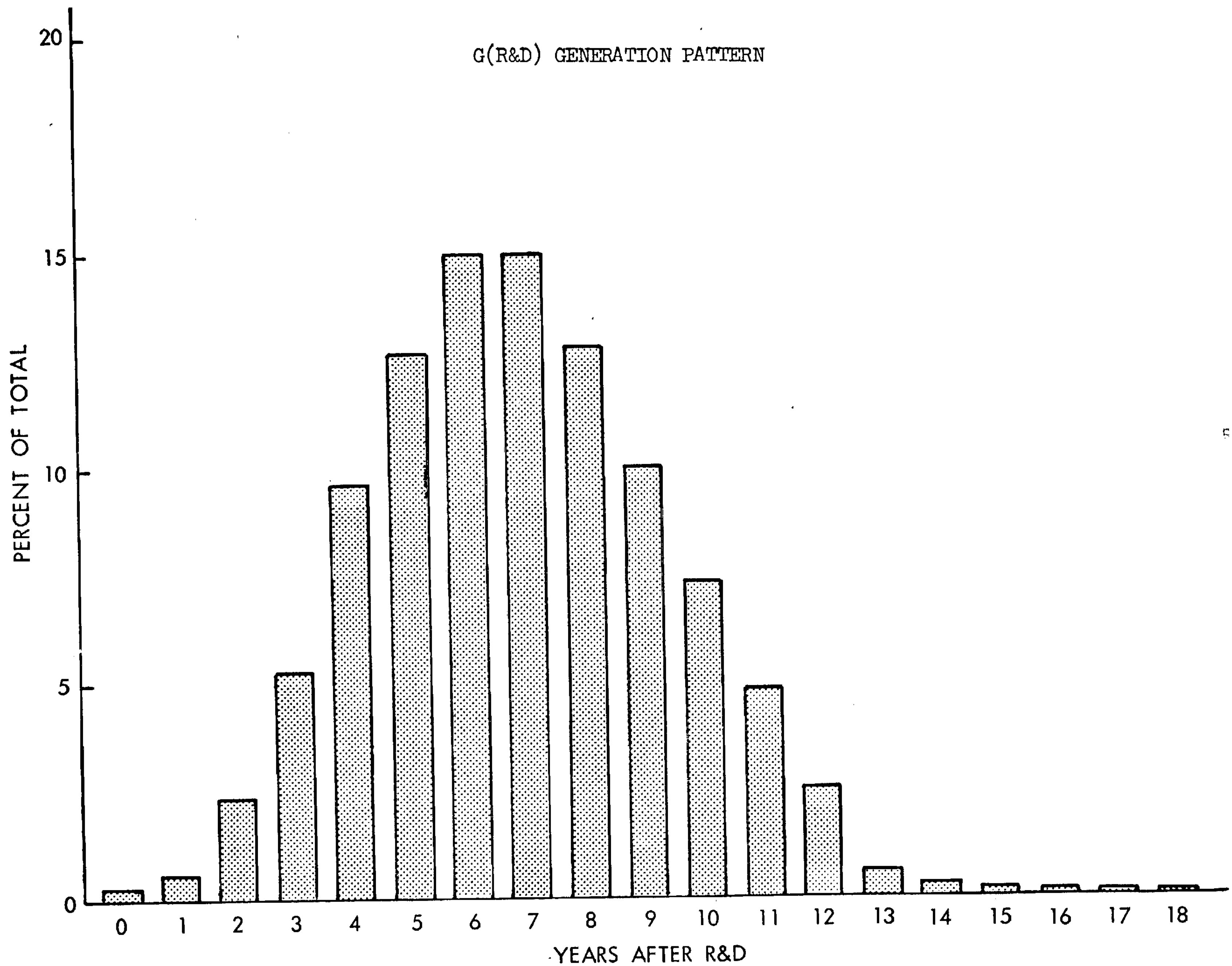
G(R&D) GENERATION PATTERN
PERCENT OF TOTAL
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
YEARS AFTER R&D

Figure 5

One interpretation of this distribution is that the yearly probabilities represent fractions of total G(R&D) contributions occurring in each of the years after R&D is performed. That is, all returns from R&D will occur within an 18-year period and approximately 75 percent of the return will occur within eight years. We will pursue this interpretation further in the next section.

The Relationship Between R&D and G(R&D). As we have demonstrated previously, a sizable portion of the increases in output due to technological progress is in fact due to the largest single determinant of technological progress--research and development. Gains in output due to R&D--which we denote G(R&D)--is in a strict cause-effect relationship with R&D. In this section, we describe the quantitative relationships between R&D and G(R&D).

We hypothesize a model in which the R&D causing G(R&D) in any time period t is given by the weighted sum of past R&D performance. The weights used are the corresponding probabilities from the G(R&D) generation distribution. Mathematically, the model is as shown below:

$$R_t = w_0 r_{t-0} + w_1 r_{t-1} + w_2 r_{t-2} + \dots + w_i r_{t-i} \dots + w_{18} r_{t-18} \qquad (1)$$

where

R_t = weighted sum of past R&D expenditures for year t,

w_i = weight for the ith year lag, and

r_{t-i} = R&D expenditures in year $t-i$.

Then, R_t is a reflection of the current year's R&D activity plus the expected value of each of the past 18 years of R&D expenditures. Conceptually, R_t could be the effective investment in R&D "at work" in year t.

Further, it is hypothesized that R_t is creating the G(R&D) observed at time t. That is,

$$G(R\&D)_t = f(R_t) . \qquad (2)$$

The functional relationship in Eq. 2 is further assumed to be a linear function of the form

$$G(R\&D)_t = a + bR_t \tag{3}$$

where

a and b are parameters to be empirically determined.1/

Using simple least-squares regression, we have estimated the parameters in (3) for the U.S. private nonfarm economy. The series for $G(R\&D)_t$ used was developed in Chapter VII for the years 1949 through 1968. The years 1955-1968 were selected for analysis because of the 18-year R&D series lead time required as a consequence of how R_t is calculated. Data for R&D expenditures do not exist (with reliability) much earlier than 1937, the first year in our series for R&D expenditures. The R&D series represents total annual U.S. R&D performance. Details of data used in the regression analysis are contained in Appendix E. The results of the regression are that

$$G(R\&D)_t = -4{,}954 + 7.23\ R_t\ .$$

The index of determination (R^2) is 0.970, indicating that 97 percent of variation in $G(R\&D)_t$ is explained by variations in R_t .

In simplest terms, the findings of this regression analysis indicate that the average dollar spent on R&D returns approximately $7.23 to the nation in the form of economic gains through technological progress, and that the return is obtained throughout an 18-year period. The discounted rate of return is 33 percent annually.2/

Figure 6 graphically shows the relationship between $G(R\&D)_t$, at any time t , and R_t --the weighted sum of past R&D. An interesting observation that can be made is the negative intercept on the $G(R\&D)_t$ axis. This indicates that unless R_t is at least $685 million, negative contributions to G(R&D) will occur. Conceptually, this would indicate a minimum R&D investment for continued positive contributions to G(R&D) .

1/ This is the general form of a straight line where a is the y-intercept and b is the slope of the line.

2/ The rate of return calculations utilize the net cash flow series and standard engineering economics methodology for calculating discounted cash flow rate of returns as described, for example, in Norman Barish, Economic Analysis for Engineering and Managerial Decision-Making (New York, New York: McGraw-Hill, 1962), pp. 147-172. Also see Appendix F.

GRAPH OF R_t VS. $G(R\&D)_t$

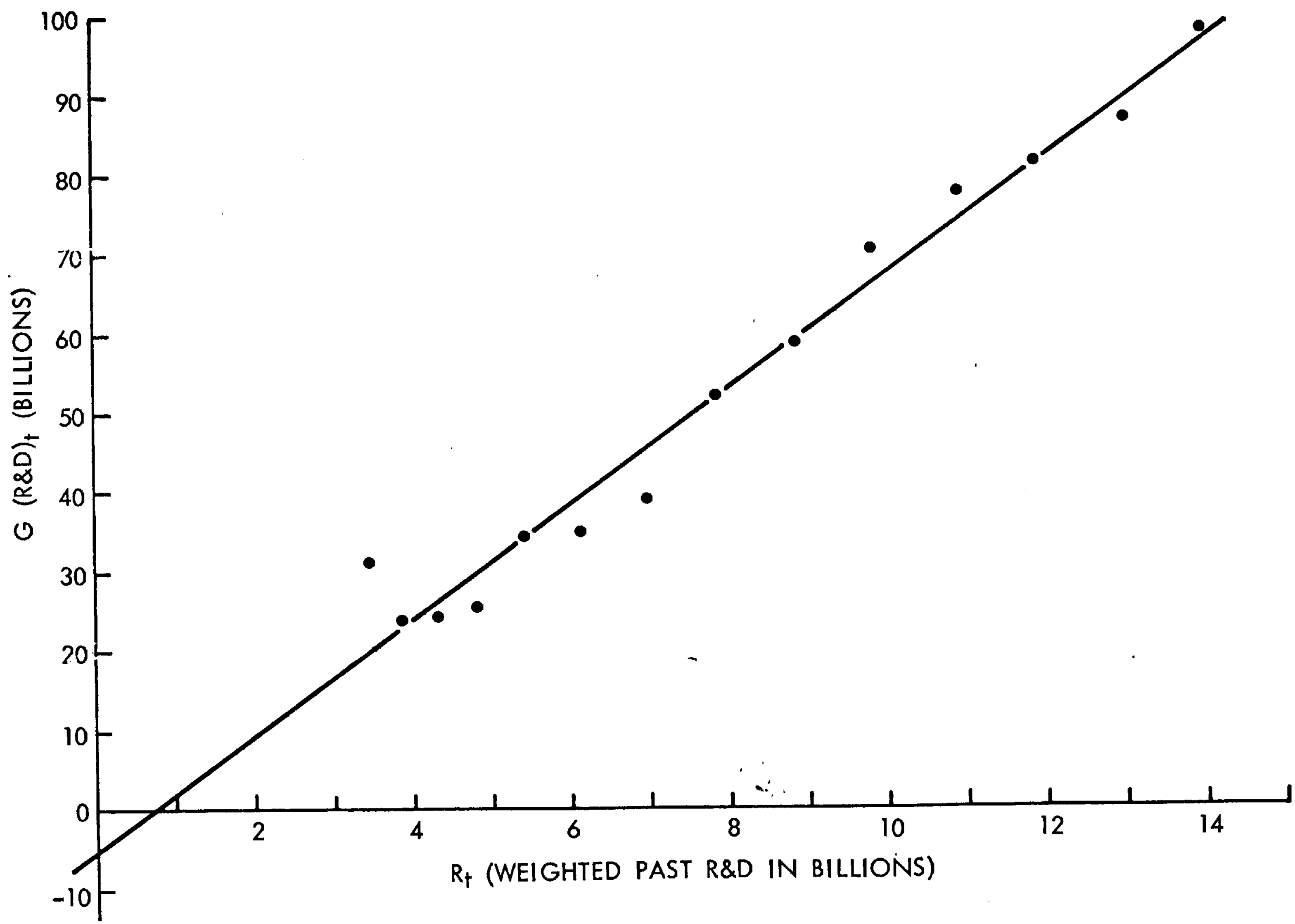

Figure 6

IX. THE ECONOMIC IMPACT OF NASA R&D ACTIVITIES

As we have previously indicated, one of the objectives of this research is to develop measures of the economic impact of NASA research and development activities. In this chapter, we will develop the NASA specific economic impact measures.

Up to this point, it has been shown that, on the average, there is an incremental addition of $7.23 to G(R&D) for each dollar spent on R&D. Further, we have shown that this return occurs over an 18-year period after the R&D is performed. It should be clear that the analysis and results represent the "typical" or average situation and, therefore, those R&D activities with higher than the average return are grouped with those of lower than the average return.

If, for the moment, it is assumed that some particular R&D activity is "typical," the models empirically developed in the previous chapter can be used to perform a projection of future long-run economic impact. That is, the expected G(R&D) stream arising from an R&D expenditure, or series of expenditures, can be brought forward. The methodology for a series of R&D expenditures will require the summation of time phased G(R&D) contributions arising from each R&D expenditure. Mathematically, the G(R&D) stream for an R&D expenditure in year t is given by:

$$G(R\&D)_{t+i} = 7.23\ w_i r_t \qquad i = 0,1,2,\ldots,18$$

where

$G(R\&D)_{t+i}$ = contribution to G in year $t+i$ arising from R&D in year t,

w_i = weighting factor for ith year from G(R&D) generation pattern, and

r_t = R&D expenditure in year t.

The annual $G(R\&D)_j$, where $j = t+i$, resulting from a time series of R&D expenditures beginning in year t_1 and ending in year t_2 would be

$$G(R\&D)_j = 7.23 \sum_{k=t_1}^{j} w_\ell \, r_k \qquad\qquad j = t_1, \ldots, t_2$$

where:

$$\ell = j - k \text{ , and}$$

$$w_\ell = \begin{cases} w_\ell & \text{if } 0 \le \ell \le 18 \\ 0 & \text{otherwise} \end{cases}$$

The annual $G(R\&D)_j$ can then be summed to provide the cumulative impact of a series of R&D expenditures.

The NASA R&D Impact. Under the assumption that R&D expenditures by NASA are no better than typical, we have applied the methodology above to the NASA R&D series for 1959 through 1969.1/ The results of the computations are presented in tabular form in Table 15 in current dollars and Table 16 in constant 1958 dollars as deflated by the GNP deflator for the 1959 through 1969 input series. It should be noted that these extrapolations do not reflect any future effects of inflation.

In Table 15, it can be seen that the $130 million of R&D performed in 1959 yields a G(R&D) stream of $1, 6, 21, etc., million beginning in 1959. The quantity for 1976--the eighteenth year beyond 1958--is not shown due to rounding. This stream is observed by reading down the 1959 column. Similarly, the 1960 expenditure of $363 million generates a stream beginning in 1960 and ending in 1977 and so on. It can be readily noted that any R&D expenditure will not create G(R&D) in a prior year nor after the eighteenth year after the expenditure by observing the blanks in the table.

The total row at the bottom of the table indicates the total impact on G(R&D) resulting from any year's R&D expenditure. The total in a column will be 7.23 (0.9871) = 7.137 times the R&D expenditure. The 0.9871 is the cumulative of the generation distribution through 18 years. That is, we have ignored 1.3 percent of the theoretical distribution which occurs after 18 years to simplify the analysis.

1/ Robert L. Rosholt, An Administrative History of NASA, 1938-1963. (Washington, D.C.: NASA, 1966), and private communication from Charles M. Hochberg, June 4, 1970.

TABLE 15

G(R&D) GENERATION PATTERN RESULTING FROM NASA R&D
(Current $'s in Millions)

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	Annual G	Cumulative G
Annual NASA R&D	130	363	630	1,334	2,622	3,610	4,416	4,878	4,015	3,811	3.226		
G (R&D) Generated													
1959	1											1	1
1960	6	2										8	9
1961	21	17	4									42	51
1962	49	59	29	9								146	197
1963	86	137	102	62	17							403	600
1964	120	240	238	216	121	24						958	1.558
1965	140	335	416	503	424	167	29					2,014	3,571
1966	140	391	582	880	989	583	204	32				3,801	7.373
1967	122	391	679	1,232	1,730	1,361	714	225	26			6.481	13.854
1968	95	342	679	1,437	2,422	2,382	1,665	788	185	25		10.021	23.875
1969	65	264	593	1,437	2,825	3,334	2,914	1,839	649	176	21	14,120	37.994
1970	41	183	459	1,256	2,825	3,890	4,079	3,219	1,514	616	149	18.230	56.225
1971	23	113	317	972	2,469	3,890	4,759	4,506	2,649	1,437	521	21,656	77,881
1972	11	63	196	671	1,910	3,400	4,759	5,256	3,709	2,515	1,216	23,707	101,588
1973	5	32	110	416	1,319	2,630	4,158	5,256	4,327	3,520	2,129	23,902	125.49[illegible]
1974	2	14	55	232	818	1,816	3,217	4,594	4,327	4,107	2,980	22,162	147.651
1975	1	6	25	117	456	1,126	2.222	3,554	3,781	4,107	3,476	18.870	166.522
1976		2	10	52	229	628	1,377	2,454	2,925	3,589	3,476	14,744	181.265
1977		1	3	21	103	315	768	1,521	2,020	2,777	3,038	10,568	191.833
1978			1	7	41	142	386	849	1,252	1,917	2,351	6,946	198.779
1979				2	14	56	174	426	699	1,188	1,623	4.183	202.962
1980					4	19	69	192	351	663	1,006	2,305	205,266
1981					1	5	24	76	158	333	561	1,158	206.425
1982						1	7	26	63	150	282	529	206,953
1983							1	7	22	60	127	217	207,170
1984								1	6	21	50	78	207.248
1985									1	6	17	24	207.273
1986										1	5	6	207,279
1987											1	1	207.280
TOTAL	928	2,591	4,498	9,523	18,718	25,772	31,526	34,824	28,663	27,207	23.050	207,280	

TABLE 16

G(R&D) GENERATION PATTERN RESULTING FROM NASA R&D
(1958 $'s in Millions)

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	Annual G	Cumulative G
Annual NASA R&D	128	351	602	1,261	2,446	3,315	3,982	4,283	3,414	3,116	2,518		
G (R&D) Generated													
1959	1											1	1
1960	6	2										8	9
1961	21	16	4									41	50
1962	48	57	28	8								141	[illegible]
1963	84	132	97	58	16							388	[illegible]
1964	118	231	227	204	113	22						915	[illegible]
1965	138	324	397	475	395	153	26					1,909	[illegible]
1966	138	378	556	832	922	536	184	28				3,574	6,978
1967	120	378	649	1,165	1,614	1,250	644	198	22			6,040	[illegible]
1968	93	331	649	1,359	2,259	2,187	1,501	692	158	21		9,250	[illegible]
1969	64	256	567	1,359	2,636	3,062	2,627	1,615	552	144	17	12,898	35,167
1970	40	177	439	1,187	2,636	3,572	3,678	2,826	1,287	504	116	16,462	51,629
1971	22	109	303	919	2,303	3,572	4,291	3,956	2,253	1,175	407	19,311	[illegible]
1972	11	61	188	634	1,782	3,122	4,291	4,615	3,153	2,056	949	20,864	[illegible]
1973	5	31	105	393	1,231	2,415	3,750	4,615	3,679	2,878	1,661	20,764	112,566
1974	2	14	53	219	763	1,668	2,901	4,033	3,679	3,358	2,326	19,016	[illegible]
1975	1	5	24	110	426	1,034	2,003	3,121	3,215	3,358	2,713	16,010	147,592
1976		2	9	50	214	577	1,242	2,155	2,487	2,934	2,713	12,384	159,975
1977		1	3	20	96	290	693	1,336	1,718	2,270	2,371	8,797	168 773
1978			1	7	38	130	348	745	1,065	1,568	1,835	5,737	174.509
1979				2	13	52	156	374	594	972	1,267	3,430	177.940
1980					4	18	62	168	298	542	785	1,878	179,818
1981					1	5	21	67	134	272	438	939	160,757
1982						1	6	23	53	122	220	426	[illegible]
1983							1	7	18	49	99	174	181.355
1984								1	5	17	39	63	181,419
1985									1	5	14	19	181,438
1986										1	4	5	181,443
1987											1	1	181.444
TOTAL	914	2,506	4,298	9,002	17,462	23,665	28,427	30,576	24,372	22,245	17,976	181,444	

The total column represents the summation of G(R&D) contributions from each of the year's R&D expenditures. In effect, it represents a yearly look at the sources of G(R&D) . For example, in 1959, G(R&D) is totally due to the 1959 expenditure appropriately weighted. However, in 1962, G(R&D) is made up of shares from 1959, 1960, 1961, and 1962 as shown in the 1962 row of Tables 15 and 16.

The cumulative total column gives the sum of the annual G(R&D) totals for any point in time. This then gives the total impact due to the expenditure series at any point in time.

Analysis of the tables discloses the following:

* The $29 billion spent on R&D by NASA during the 1959-1969 period will yield a positive contribution to G(R&D) of $207 billion through 1987.

* Through 1970, the 1959-1969 R&D expenditures by NASA have generated a G(R&D) of $56 billion or 1.93 times the original expenditure.

* Similar results follow from analysis of the 1958 constant dollar table.

Numerous other results can be gleaned from the tabular results. To further illustrate the flows of G(R&D) , we have depicted the distributions of flows resulting from each year's R&D in a time sequenced relationship in Figure 7. Summation of the ordinates for each curve would yield the totals as shown in the next to last column in Table 15. As is readily apparent from Figure 7, the generation process, when a series of R&D expenditures is involved, is complex.

In order to further analyze the economic impact of the NASA R&D expenditures, we have calculated the <u>net</u> flow for the 1959 through 1987 period by discounting annual G(R&D) by the R&D expenditure in the same year. Figure 8 illustrates the net flow. Performing a rate of return calculation on this series yields an annual discounted rate of return of 33 percent.[1]

<u>How Typical is NASA?</u> The analysis of the preceding section depends upon a critical assumption--NASA R&D expenditures generate the same G(R&D) stream as the <u>average</u> R&D expenditure. In this section, we show that this is a conservative assumption and that the G(R&D) stream created by NASA R&D should, in fact, be higher than the average.

1/ See Appendix F for complete discussion of rate of return calculations.

THE G(R&D) STREAMS FROM NASA R&D SERIES
(1959-1969)

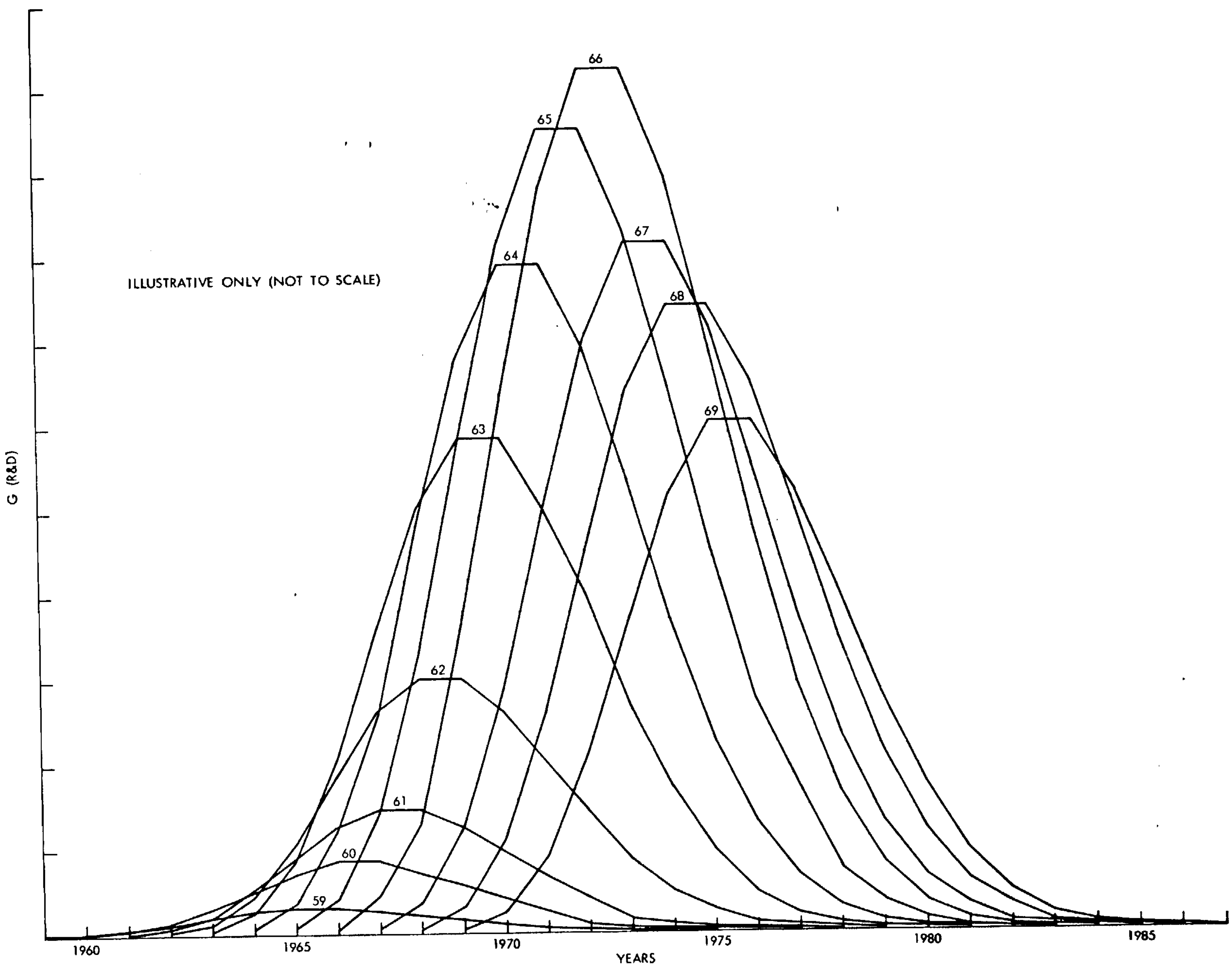

Figure 7

NASA R&D EXPENDITURES
(Constant 1958 dollars)

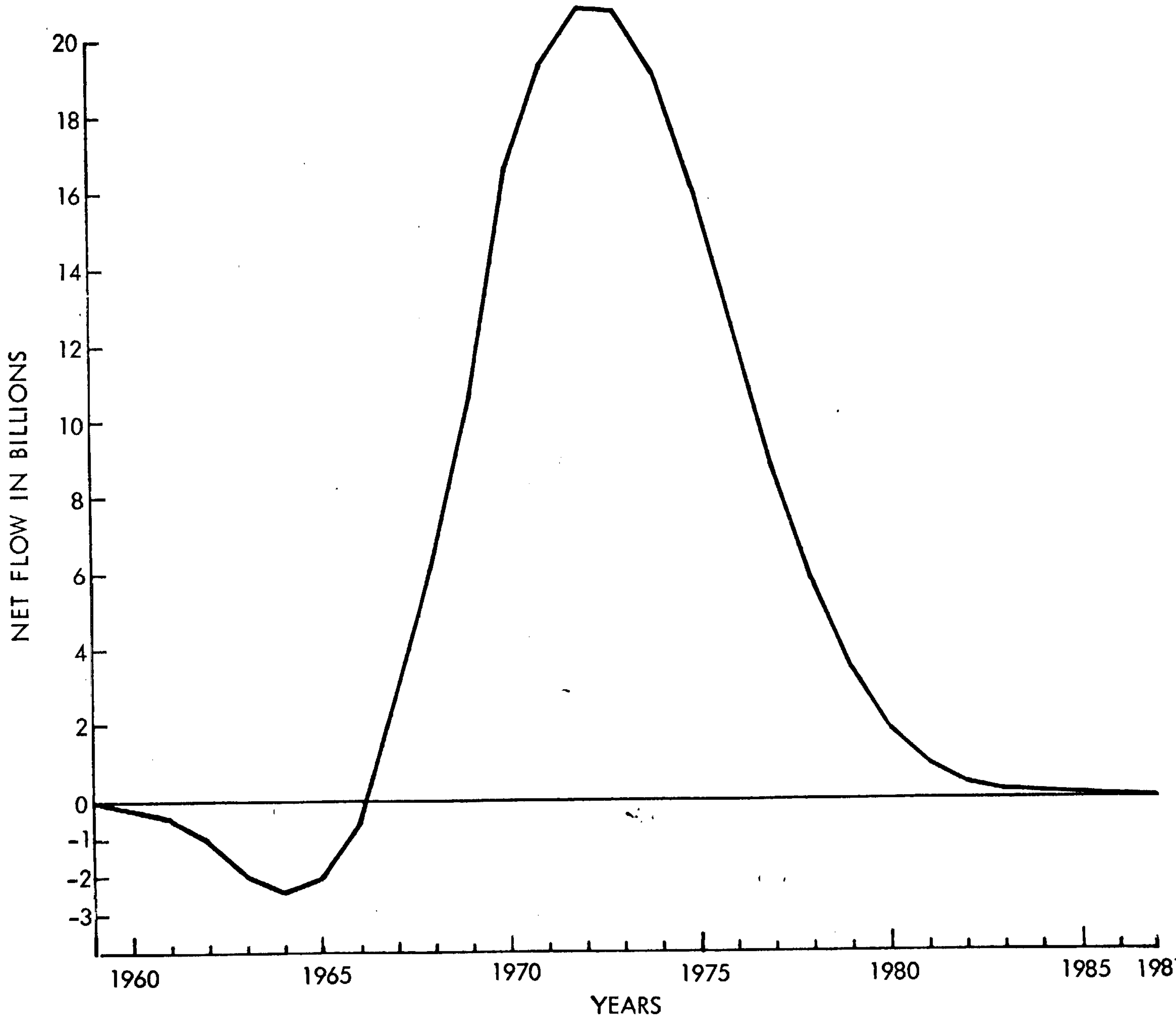

Figure 8

In order to obtain quantitative estimates of how non-typical the NASA R&D returns may be, an industry level analysis of technological progress was performed. The analysis consisted of applying the Solow methodology to each two-digit SIC code manufacturing industry and all manufacturing for the period 1949-1967. The methodology, data, and detailed results are included in Appendix G. Table 17 shows the level of technology, A_t, being applied in 1966 for each industry. It can be seen that the manufacturing sector has a wide range of A_t among the two-digit industries.

Since A_t can be interpreted as the technology multiplier; that is, output is equal to total factor inputs times A_t, it is readily evident that resources allocated to one industry can have significantly different "leverage" than in another industry. Output is then clearly a function of the mix of expenditures by industry. From Table 17, the total inputs into the manufacturing sector yielded an average technology multiplier of 1.4331 in 1966 relative to the 1949 technology level. In other words, every dollar, distributed according to the 1966 expenditure pattern, yielded $1.43 output or $.43 more than would have been experienced in 1949. Analysis of alternate spending distributions could, within limits, be used to investigate relative multiplier effects.

Based on the 1966 mix of NASA spending levels in the manufacturing industry, an analysis of technological leverage obtained by the NASA spending pattern is possible. Table 18 is an analysis of fractions of total NASA expenditures going to those industries NASA primarily dealt with. The weighted A_t resulting from the manufacturing sector expenditures is 2.122, indicating a significantly higher multiplier than the total U.S. economy spending pattern in the manufacturing sector in 1966. One is led to the inevitable conclusion that the pattern in which NASA resources are distributed leads to significantly higher applied A_t and, therefore, a significantly higher G(R&D) than the average spending pattern.

The foregoing conclusion is only an indication that the return from NASA is higher than the average and attempts to interpret quantitative differences should be handled with caution. The reasons for this are manifold. Some are:

1. The Solow methodology does not have full applicability for <u>precise</u> A_t calculations at the industry level.

2. Data at the industry level require numerous assumptions and estimates.

3. The weighted A_t is a limited attempt (consistent, however, with the overall limitations of this analysis) to treat aggregation.

NASA R&D EXPENDITURES
(Constant 1958 dollars)

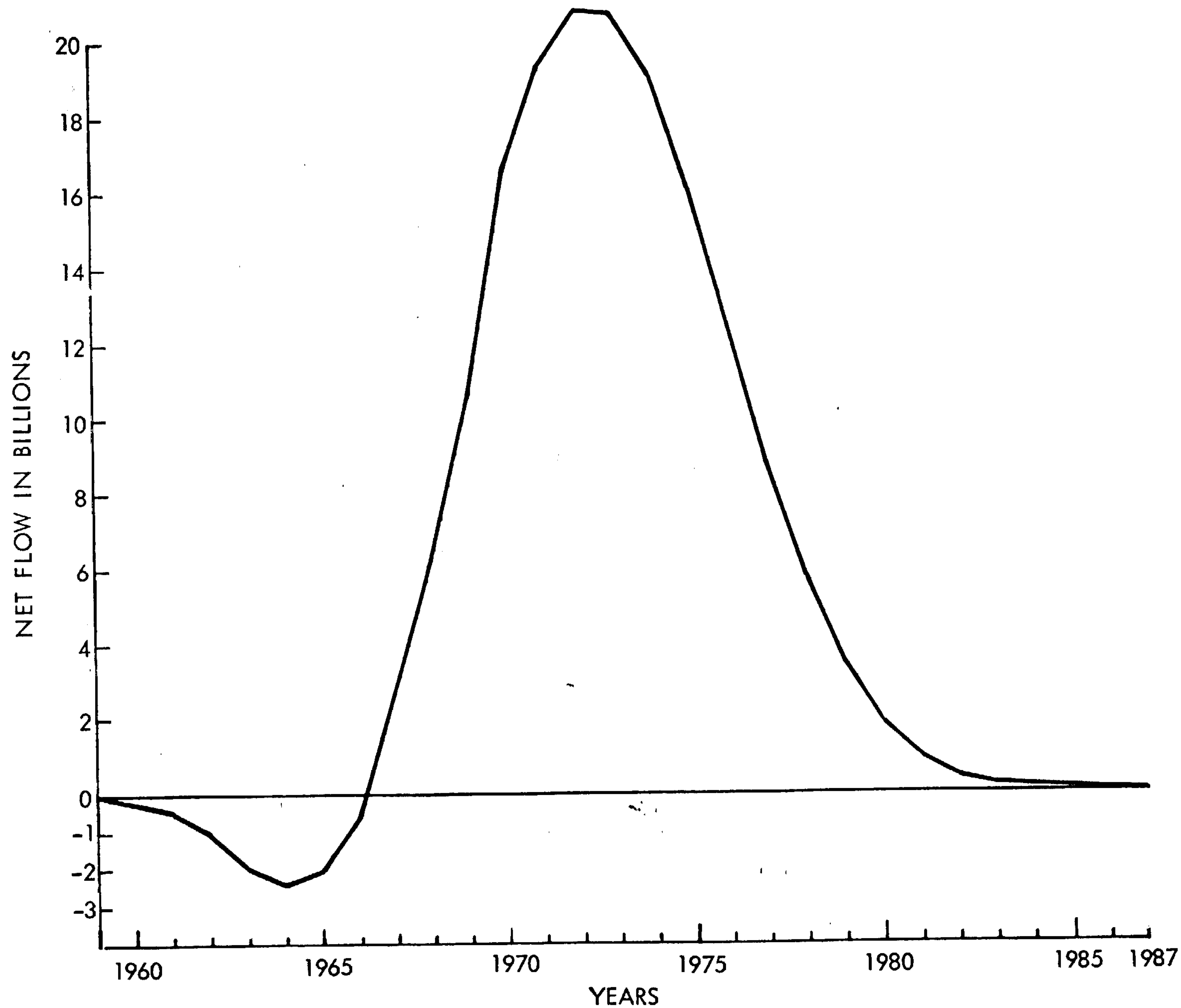

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TABLE 17

1966 INDUSTRY TECHNOLOGY LEVELS

SIC		A(1966)
20	Food and kindred	1.3997
21	Tobacco	0.9051
22	Textiles	1.3338
23	Apparel	0.9996
24	Lumber and wood	1.5058
25	Furniture	1.7788
26	Paper and allied	1.3604
27	Printing	1.5797
28	Chemicals	1.8025
29	Petroleum refining	1.8403
30	Rubber and plastics	1.2003
31	Leather	1.4818
32	Stone, clay and glass	1.4969
33	Primary metals	1.8302
34	Fabricated metal	1.7826
35	Machinery, except electrical	2.2382
36	Electrical machinery	1.5580
37	Transportation equipment	2.1831
38	Scientific instruments	2.1570
Total Manufacturing		1.4331
NASA		2.1224

TABLE 18

FISCAL YEAR 1966 NASA EXPENDITURES

SIC	Expenditure ($000)	Percent of Total
192	1,330,795	32.1
Rest of 19	7,602	0.19
3722	485,899	11.7
3721 & 3729	1,442,467	34.8
3721 & 3722	143,550	3.5
Rest of 37	6,571	0.16
27	2,853	0.07
28	96,054	2.3
29	1,727	0.04
30	2,444	0.06
33	4,038	0.10
34	15,248	0.40
357	206,114	5.0
Rest of 35	18,642	0.45
366	316,712	7.6
Rest of 36	35,644	0.87
38	27,004	0.66
Total	4,143,364	100.0

Source: Lloyd D. Orr and David Jones, An Industry Breakdown of NASA Expenditures, Indiana University, Bloomington, Indiana, November 1969.

In spite of these limitations, it is clearly evident that the NASA economic impacts quantified in this research do, in the worst case, represent absolute lower bounds. Extensive further research is required to improve the precision of these results.

Two potential areas for additional research, consistent with the basic approach pursued above, are:

1. More definite assessments of industry level technological progress through the use of more complex production functions--e.g., CES or VES forms--and refined data on capital in existence, utilization rates, value added deflators, etc. It should be noted that both the model and data warrant simultaneous improvement to preclude inconsistencies in reliability of these two aspects of the assessment process.

2. Refinement of the aggregation procedure used to determine the economic leverage resulting from a real or hypothetical spending pattern.

APPENDIX A

TECHNOLOGY AND ECONOMIC GROWTH: BASIC CONCEPTS AND REVIEW OF RECENT RESEARCH

1. TECHNOLOGICAL PROGRESS IN THE HISTORY OF ECONOMIC THOUGHT

Technological change has long been recognized as one of the dynamic factors in economic growth, but only in recent years has it been considered of outstanding importance, and only recently have attempts been made to measure its impact.

Technological Progress in Economic Theory

Most of the past economists recognized the existence of technological change, and mentioned it as a factor in their dynamic economic models. However, it was usually considered of secondary importance compared to capital accumulation, and its dynamic effects were more often viewed as an explanatory variable in business cycles than as a factor contributing to long term economic growth.

The view of Adam Smith was that the primary source of growth was capital accumulation, and secondarily an improved division of labor. But he did suggest that a link between these factors and technological change did exist. According to Smith the "measured" sources of growth were as follows:

> The annual produce of the land and labour of any nation can be increased in its value by no other means, but by increasing either the number of its productive labourers, or the productive powers of those labourers.[1]

However, the reason why labor inputs would be increased was an increase in capital. The sources of increased labor productivity were an improved division of labor, or "Some addition and improvement to those machines and instruments which facilitate and abridge labour."[2] This does indicate the

1/ Adam Smith, An Inquiry Into the Nature and Causes of the Wealth of Nations (N. Y.: The Modern Library, 1937), p. 326.

2/ Ibid., p. 326. Smith also indicated that the division of labor was a factor which contributed to technical progress, for workers saw where improvements could be made. Again, he did consider only improvements in machinery.

awareness of technological progress, but of a kind restricted to improvements embodied in new machinery. And, it was of decidedly secondary importance as a growth factor, with the emphasis being on capital accumulation as summarized in the following statement.

> When we compare, therefore, the state of a nation at two different periods, and find, that the annual produce of its land and labour is evidently greater at the latter than at the former. . .we may be assured that its capital must have increased during the interval . . .1/

Ricardo also discussed the growth potential of technological change, and like Smith emphasized improvements in machinery. In fact, his discussion of technical change is restricted almost entirely to a chapter entitled "Machinery."2/ In that chapter he argues that "the discovery and useful application of machinery always leads to the increase of the net produce of the country."3/ However, he did feel that the gross product could be diminished, and implied that a major impact of technical change is likely to be on income distribution.

> . . .the employment of machinery is frequently detrimental to their [the labouring class] interests.4/

Even Malthus, who, it is commonly viewed, overlooked technical progress in making his gloomy predictions regarding the increase of food and population, realized the existence of this source of growth. However, such a factor did not deter his conclusion for he believed that improvements in machinery occurred only in response to demand, and the effect on the supply of output would never outrun the increase in demand, but would serve only to stave off some lower level of subsistence.5/

Technological progress was also mentioned by any number of earlier economists,6/ but most never believed it to be of any great consequence, particularly as it might affect the output of an industry or a nation. The emphasis was on improvements in machinery that were labor-saving. As such

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1/ Ibid., p. 326.

2/ David Ricardo, The Principles of Political Economy and Taxation (N. Y.: Everyman's Library, 1948), Ch. XXXI.

3/ Ibid., p. 267.

4/ Ibid.

5/ Thomas R. Malthus, Principles of Political Economy, 2nd ed. (London: William Pickering, 1936), pp. 309-413.

6/ Including Marshall, Mill, and a host of lesser known economists such as Condorcet and Godwin.

the effects were viewed as affecting income distribution more than growth of output. The opinions were mixed, of course, some viewing such technical change as easing the burden of labor, while others viewed it as damaging to the laboring class. On this latter side we must of course mention Marx who believed that technical change was the response of capitalists to declining profit rates, and as such would serve to create an army of technologically unemployed.

Perhaps the only economist of stature to discuss at any length what we now call technological progress is Joseph Schumpeter. Schumpeter was primarily concerned with the dynamic forces in the economy and devoted his works to such discussion. To him the area of economic analysis requiring work was that explaining changes in the parameters of the system, which meant the economy had been redirected toward a different equilibrium position. He viewed this as economic development, and in his explanation of such economic change the entrepreneur and innovator, and of necessity the innovations, were essential.1/

But, for the most part, economists have treated technology as a parameter and examined the short-run features of a system constrained by a level of technology. In comparative static analysis some attention has been devoted to the consequences of a change in the level of technology. In the very recent past, however, with developments occurring in a sector of economics entitled growth theory, more attention has been given to technological progress. In part, the recent attempts at measuring the aggregate effect of technological change spring from the developments in the use of the aggregate production function in growth theory.

Technological Progress In Economic History

While theorists discussed the role of technical change they rarely gave it an important place. Economic historians, however, in discussing the industrial revolution, or the take-off, and in trying to explain long-term economic growth, necessarily gave greater emphasis to technological change than did the theorists. However, technological change has never been precisely defined in its fullest meaning, and measurement of the impact of such change has never been in terms of all its attributes.

1/ See his following works, The Theory of Economic Development (N. Y.: Oxford University Press, 1961); Capitalism, Socialism and Democracy (N. Y.: Harper and Row Publishers, Inc.--Harper Torch Book Edition, 1962); Business Cycles (N. Y.: McGraw-Hill, 1964).

The earliest approaches to assessing the role of technological change, other than the minimum discussion of Smith or Marshall, defined and explained the industrial revolution in England.1/ For the most part, this consisted of cataloguing the detailed changes that had occurred in the technology of several industries crucial to the revolution. Researchers traced the origins and consequences of the development of the steam engine and of the series of advances in the textile and metal working industries. However, the impact of these changes was never well measured. The growth of the industries involved was documented, the success of some prominent individuals was described, and the potential reduction in labor inputs was often suggested.2/ But, it was never proven how much of the industry's growth was attributable to new technology. It was not always shown that the labor savings actually occurred, and were greater than the capital costs. And, the impact in one industry was only obliquely assessed in terms of the entire economy.

This approach has not been entirely abandoned. It has, however, been augmented by studies which try to more precisely measure the economic consequences. Until only quite recently, however, the measurements were confined to the impact in particular industries, although several researchers tried to survey the advances in an entire industrial sector.3/ For example, Clark cites many advances in manufacturing, and gives a specific measure of its effect in that industry or firm.

> Meanwhile improvements in printing machinery helped to promote the consumption of paper. . . During the war a Pittsburgh inventor perfected a press into which paper was fed continuously from a large roll, and which printed both sides simultaneously at the rate of 9,000 sheets per hour. (Vol. II, p. 133.)

1/ See for example, Paul Mantoux, The Industrial Revolution in the Eighteenth Century (N. Y.: Harper and Row Publishers, Inc.--Harper Torch Book Edition, 1962); John H. Clapham, An Economic History of Modern Britain (Cambridge: Cambridge University Press, 1926-38), 3 Vols.; or more recent works, P. Deane, The First Industrial Revolution (Cambridge: Cambridge University Press, 1965); T. S. Ashton, The Industrial Revolution (London: Oxford University Press, 1960).

2/ The sociological and political consequences were also discussed.

3/ See for example, V. S. Clark, History of Manufactures in the United States (Washington, D. C.: Carnegie Institution of Washington, 1916), Vols. 1, 2, and 3; or Leo Rogin, The Introduction of Farm Machinery in Its Relation to the Productivity of Labor in the Agriculture of the United States During the Nineteenth Century (Berkeley, Calif.: University of California Press, 1931).

> . . .by 1875 power mules had almost entirely replaced (the self operating jack). The result was to lower the cost of spinning and to increase the output per spindle by one half. . .(Vol. II, p. 112).

Much of the work on specific inventions or industries suffers from a failure to deal with all the other changes that were occurring, and therefore may have attributed to technology some consequences that perhaps derived from other factors.

More recent work has tried to eliminate the effects of these other factors, and thereby arrive at a more precise measure of the impact of technological change, and determine its relative importance. William Parker and Judith Klein have sorted out the effects of several variables on the course of output per worker in grain production in the United States between 1840 and 1910.1/ In a very detailed way, they assessed the effect of the shifting location of production, primarily the westward movement, from that of technological change. They concluded from analyzing the remaining productivity gains that "mechanization was the strongest direct cause of the productivity growth in the production of these grains."2/ Similar studies have been conducted for other industries, and industrial sectors, and with few exceptions reach the conclusion that technological progress was important.3/ The exceptions are typically in the service industries, and here one finds that the productivity of the classical factors of production is increasing, but often because the consumer is doing more work.4/

1/ William Parker and Judith Klein, "Productivity Growth in Grain Production in the United States, 1840-60 and 1900-10," in Output, Employment and Productivity in the United States After 1800 (New York: National Bureau of Economic Research, 1966).

2/ Ibid., p. 543.

3/ Even some exceptions can be viewed as technical progress. The major source of increased output per worker in dairying during the Nineteenth Century was an increase in the annual output per cow. This increase was not due to new technology, but primarily to the diffusion of existing technology. Some people, however, view diffusion as part of the process of technological change. See F. Bateman, "Improvement in American Dairy Farming, 1850-1910: A Quantitative Analysis," and "Labor Inputs and Productivity in American Dairy Agriculture, 1850-1910," in Journal of Economic History, Volumes XXVII and XXIX.

4/ David Schwartzman, "The Growth of Sales per Man-Hour in Retail Trade, 1929-1963," in V. Fuchs, ed., Production and Productivity in the Service Industry (New York: National Bureau of Economic Research, 1969).

Most of this work, while an improvement in measuring technological change and assessing its relative importance in explaining productivity growth, failed to relate the change within an industry to growth in the entire economy. Recent analysis of technological change focuses on this aspect of its consequences. This final approach has developed along with advances in the body of economic theory and econometrics.

The Changing Concept of Technological Change

From this brief review of technological change as an explanatory variable of long-term economic change, we can see that the concept has undergone revision and expansion. The classical economist viewed the level of technology as being the state of the art in machinery. Therefore, technological change meant improvements in machinery. Explorations of the industrial revolution were apparently guided by this concept and yielded detailed chronologies of innovations, but little measurement of impact. Subsequent work in economic history was concerned with measuring both the absolute and relative effects of technological change on an industry's output and productivity. In the course of such measurement the concept of technological change was sharpened.

As we noted earlier, Parker and Klein estimated that mechanization was the single most important source of productivity change in grain production. But, another source of productivity change was that of non-mechanical technological improvements. Improved variety of seeds, better fertilizer and better knowledge regarding crop planting, harvesting and rotation increased the yield per acre. In dairy farming, the most important source of increased milk output per cow was the lengthening of the milking season. Those kinds of advances are far removed from the earlier notion of technical change which embodied scientific advances in new machinery. This latter type, now called disembodied technical change, is less dramatic, and its effects are perhaps less apparent in the statistical evidence.1/

The concept of technical change has also been sharpened by research which has gone beyond the dramatic inventions familiar to most people. Early studies of the industrial revolution emphasized the role of the steam engine, and a series of well known developments in the textile industries. For a long time, U.S. economic historians emphasized the major innovations

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1/ In Bateman's study the source of increased productivity was the diffusion of this known technique. However, at some earlier date someone discovered that cows could be milked longer, and so this new technique was available to all for use without having to embody it in new capital equipment. Parker and Klein asserted that such technical change was less apparent. (op. cit., p. 543.)

in industry. This approach, however, is naive. We know now that technological change "was really an endless sequence of improvements made by unknown skilled and professional workers."1/ For example, studies of productivity advance in the U.S. textile industry after 1824 indicate that new machines did appear and increase productivity, but they were not the only source of productivity advance.2/

> More important, throughout the period new refinements were worked out in the machine shop and then were incorporated in the latest models of the old machine.

Similar evidence has been compiled for other industries.3/

These changes in our understanding of technical change, and an improved understanding of the process by which technical advances get into the economic system, have created difficulties in trying to assess the impact of a particular innovation.4/

1/ D. North, Growth and Welfare in the American Past (Englewood Cliffs, N. J.: Prentice-Hall, 1966), p. 157.

2/ Lance Davis and H. Louis Stettler, "The New England Textile Industry, 1825-1860: Trends and Fluctuations," in Output, Employment and Productivity in the United States After 1800 (New York: National Bureau of Economic Research, 1966), pp. 229-230.

3/ See the following works: Thomas R. Navin, The Whiten Machine Works Since 1831 (Cambridge: Harvard University Press, 1950), p. 405. Samuel Hollander, The Sources of Increased Efficiency: A Study of Du Pont Rayon Plants (Cambridge: The MIT Press, 1965). H. F. Williamson, R. L. Andreano and Carmen Menzes, "The American Petroleum Industry," in Output, Employment and Productivity in the United States After 1800 (New York: National Bureau of Economic Research, 1966). Perhaps this is an appropriate point to mention the important work of Jacob Schmookler, who tried to determine the rate of technical change by examining patent records. It is thus an attempt to relate inventions to the aggregate economy. (See, Jacob Schmookler, "The Level of Inventive Activity," The Review of Economics and Statistics, 36 (May 1954), pp. 183-190, and "Inventing and Maximizing," American Economic Review, 53 (September 1963), pp. 725-729.) His work is being pushed in new directions by William Nordhaus at the Cowles Foundation for Research in Economics at Yale University.

4/ The difficulties of measuring the impact of a single innovation can be compounded not only by a delay in diffusion, but by the eventual diffusion to unrelated industries. The machine tool industry offers evidence of the interrelationships among industries. See, N. Rosenberg, "The Technological Change in the Machine Tool Industry, 1840-1910," Journal of Economic History, 23 (December 1963), pp. 414-443.

The newer aggregate production function approach overcomes some of these problems. No attempt is made to identify the technical advances that occurred. By restricting enquiry to a specified time period, the researcher need not consider the effects of diffusion that occur after the closing date. As we noted, however, if the residual is precisely measured in these studies, the resulting value, while often large, pertains only to the supply side. Thus, while it is an improvement to rigorously quantify the impact of a well defined conception of technical change, the result is limited by such methodological precision. While economic historians did not make a measurement of this aggregate effect, they did develop a broader view of the meaning and impact of technological change. A concise summary, subject to some of the refinements discussed, is provided by Victor Clark.

> Technical progress arises from the effort of industry to enlarge production, improve products, economize labor and materials, utilize new substances, and produce a greater variety of articles for consumption.1/

All of these effects cannot be captured in a residual measure of increased output. The impact of technical change falls on the demand side of the equation as well as the supply, and both the demand and supply effects need not result in increased output, nor be identifiable as the source of increased output.

2. PRODUCTION THEORY

Production Function Concepts

Central to total factor productivity measurements is the concept that productivity can be computed by using the equation:

$$P_T = \frac{Q}{\alpha L + \beta K},$$

where P_T = Total factor productivity,

Q = Output,

K = Capital input,

1/ Clark, op. cit., I, p. 402.

L = Labor input, and

α, β = Weighting factors.

This implies a production function of the form

$$Q = P_T (\alpha L + \beta K). \tag{1}$$

From a purely mathematical standpoint, this function will yield a positive value for Q if either K or L is equal to zero. That is, either labor or capital can yield output autonomously. This difficulty, among others, has led economists to construct alternative mathematical specifications or functions which can more realistically describe the output generating process. Before describing some of these approaches it might be useful to explore some characteristics that a production function should possess in light of the neoclassical theory of production.

As Murray Brown[1/] has pointed out, a minimal set of three criteria must be satisfied. First, the marginal products of factors must be positive. That is,

$$\frac{\partial Q}{\partial K} > 0 \quad \text{and}$$

$$\frac{\partial Q}{\partial L} > 0 .$$

This criterion is met by (1) in that:

$$\frac{\partial Q}{\partial K} = \beta P_T \quad \text{and}$$

$$\frac{\partial Q}{\partial L} = \alpha P_T .$$

The second criterion requires that, over a relevant range, each marginal product should decrease when labor and capital increase. Symbolically, this requires that

$$\frac{\partial^2 Q}{\partial K^2} < 0 \quad \text{and}$$

1/ Murray Brown, On the Theory and Measurement of Technological Change (N. Y.: Cambridge University Press, 1968).

$$\frac{\partial^2 Q}{\partial L^2} < 0 .$$

For (1), the criterion is not met in that

$$\frac{\partial^2 Q}{\partial K^2} = 0 \quad \text{and}$$

$$\frac{\partial^2 Q}{\partial L^2} = 0 .$$

Conceptually, the marginal products do not change through ranges of K and L.

Third, a production function should not determine economies of scale on an _a priori_ basis. From a mathematical standpoint, the function should be capable of assuming any degree of homogeneity empirically dictated. A production function is homogeneous of degree n if and only if

$$f(\lambda L, \lambda K) = \lambda^n f(L,K).$$

In the case of (1),

$$Q = P_T\,[\alpha(\lambda L) + \beta(\lambda K)] = \lambda P_T(\alpha L + \beta K)$$

and therefore, (1) is homogeneous of degree 1 which implies constant returns to scale. Hence, the production function implicit in productivity measurements fails two of the three neoclassical requirements.

Production functions that do satisfy the requirements have been constructed and empirically investigated. The most famous and widely used function is attributed to Cobb and Douglas.1/ The Cobb-Douglas function is of the form

$$Q = P_T L^{\alpha} K^{\beta} \quad . \tag{2}$$

Brown shows that this function satisfies the three criteria outlined above if α and β are independently determined. That is, if $1 - \alpha = \beta$ is

1/ See Brown, _op. cit._, for more extensive discussion of the Cobb-Douglas function.

not required to hold--which would fix economies of scale at unity since (2) is homogeneous of degree $\alpha + \beta$. Nevertheless, there is an inherent difficulty with (2).

Without becoming entangled in difficult mathematics here, let us merely state that it can be shown that (2) has an elasticity of substitution of labor for capital equal to one for all empirically developed values for α and β. From a conceptual standpoint, this can be interpreted to mean that relative shares of income to capital and labor are constant for any changes in the relative supplies of labor and capital. This is a famous property of the Cobb-Douglas function and one that has precipitated the development of production functions that do not possess this property. These are referred to as "constant elasticity of substitution," (CES) and "variable elasticity of substitution," (VES) functions. These improved functions are more important in inter-industry comparisons than in aggregate analysis. More important, empirical results show that with the CES functions, empirically developed elasticity of substitution is close to one for the U.S. economy. 1/

The Residual

The major obvious difference between (1) and (2)--and the more complex production functions for that matter--is that the factors of labor and capital are multiplicative rather than additive. They all have, in one form or another, the multiplier P_T. This is referred to as either total factor productivity or alternatively as the "index of technology" or the "residual." Irrespective of the terminology, P_T compensates for any variations of true output from that calculated by the production function or source data for an index number computation. We will refer to it as the residual.

The residual measures the output not explained or caused by the inputs--that is, in the way the inputs are said to interact and contribute to output as specified by the production function used to calculate P_T and also based on the data series for the inputs.

1/ Brown, op. cit., includes work by him and DeCani that yields essentially the same results in aggregate analysis when comparing a CES and Cobb-Douglas model. Lester Lave cites work by Nelson, which led to similar results in Technological Change: Its Conception and Measurement (Englewood Cliffs, N. J.: Prentice Hall, 1966).

The production function of the form:

$$Q = f(L,K,P) \tag{3}$$

where we have replaced P_T with a more general productivity component, P, can take on a number of functional forms. This is primarily because of the flexibility that the state of the art allows.

Depending on whether the increases in productivity are felt to be exogenous to capital and labor inputs or endogenous to them, (3) will take on the following forms, respectively:

$$Q \doteq P_T \, f(L,K) \tag{4}$$

or

$$Q = P_T' \, f[f_1 \, (P_L,L), \; f_2 \, (P_K,K)] \tag{5}$$

In (4), the assumption is that increases in productivity are disembodied and in (5) the pure labor and capital series are "adjusted" to reflect embodied productivity gains. Disembodied productivity gains of P_T' are also included in (5). In either case, a man-hour of labor or a dollar of capital is producing more or less output, as the case may be, which is reflected in the productivity factors of the function.

3. QUANTIFYING TECHNOLOGICAL PROGRESS--TWO APPROACHES

Recent literature on economic growth is liberally endowed with both theoretical and empirical studies aimed at measuring the sources of economic growth. Because of its widely recognized importance as such a source, a focal point of many of these studies is technological progress.

The Task

The central question to be answered is simply how much additional output, measured in gross national product, results from a given level of factor inputs at some one point than at some earlier point in history? If an increase in output has occurred with no increase in factor inputs, then productivity has advanced. Furthermore, if income per capita has increased, then welfare has also improved, at least in general. This advance in productivity and welfare can be attributed to technological progress, certainly in its broadest sense, because productivity has changed with no direct increase in either labor or capital used to generate the output.

Two General Avenues

In quantifying the technological component of growth--that is, growth beyond that attributable to increases in factor inputs--economists have approached the problem from basically two fronts--through quantification of productivity increases, as measured by an index such as output per man hour, and through production theory models. In the former approach, changes in productivity indexes are implicitly assumed to reflect the effect of such external forces as technological progress. The production theorist, on the other hand, typically attacks the problem more directly, in that he simply defines the unexplained changes in growth as technological progress, _a priori_. On balance, the distinction is academic, since both approaches treat that contribution to growth which is unexplained by changes in factor inputs as arising from an external force which is commonly referred to as "technological progress."

Practical Problems of Estimation

Regardless of the approach used, there are three problems of estimation that must be recognized:

* First, the effects of technological progress are measured entirely by growth of output which is unexplained by change in factor inputs. The consequence of this, of course, is that the products of any factor inputs that are either not specifically treated as factor inputs or go unrecognized are simply lumped within the resultant measure labeled technological progress.

* Second, use of gross national product (or net national product) as a measure of output has several difficulties associated with it. Among these is that it fails to capture some of the more important collateral benefits of technological progress such as new or improved final products, less expensive final products, and so on.

* Third, as Mansfield has pointed out, such gross measurements fail to give adequate recognition to the substantial degree of interdependence among technological progress and the nontechnological or quasi-technological factors, such as education, changes in worker health and morale, and the like. As a result, the estimated contribution of each of these latter factors may not be an adequate indication of the synergistic effect on the growth rate that would actually result from additional emphasis on any one of them.

Introduction to Sections 4 and 5

In Sections 4 and 5, we will describe something of the methodologies, the underlying theoretical bases, and the problems within each of the two general approaches, and will present a representative sampling of recent results. It is not intended that this be a comprehensive review of the research performed to date, nor a tutorial on the measurement of technological progress. Rather, our objective is simply to describe more fully the leading approaches to quantification of technological growth, and indicate some of the results obtained with each of these approaches.1/

4. MEASURES OF TECHNOLOGICAL PROGRESS: PRODUCTIVITY CHANGES

Productivity Measures

Productivity Defined. The term productivity is generally used to denote the ratio of output to any or all inputs used in creating that output. This brief but convenient definition will easily serve our purpose here.

Partial Productivity Measures. Ratios such as output per man-hour or output per dollar of capital are usually termed "partial productivity measures." This is because partial productivity ratios do not adequately measure overall changes in productive efficiency, since factor substitutions which can also increase output are not necessarily differentiated. For example, if in a given period a substitution for capital is made which increases output, the labor productivity will increase for two reasons. First, an increase in output has been occasioned by increase in capital and, second, the substitution of capital for labor has reduced labor inputs. The effect is a double attribution to labor productivity of the gains actually resulting from capital increases.2/

Measurement by Residual--Total Factor Inputs as a Stepping Stone

To circumvent this inherent difficulty, productivity can alternatively be measured by use of total factor inputs, which are then subtracted from total outputs to reveal a residual attributable to productivity.

1/ For a more detailed review of the underlying literature, the reader will find the two sources cited in footnote 3 to Chapter I, and also A. A. Walters, "Production and Cost Functions: An Econometric Survey," ECONOMETRICA, January-April 1963, of particular value. For additional theoretical background, see Murray Brown, op. cit.

2/ See Brown, op. cit., Chapter 7, for theoretical investigation of productivity ratios, their meaning, and measurement capabilities.

Kendrick [1] has performed the most comprehensive analysis of productivity gains in the context of total factor inputs. In general methodology, the work by Kendrick is not unlike the pioneering work by Abramowitz [2] and the British-American industry comparisons by Salter. [3] It is, however, a more comprehensive look at productivity gains in the U. S. economy than either of the other two works.

Fabricant, [4] in his "Basic Facts on Productivity Change," has given an excellent summary of Kendrick's work, which can be recounted as follows:

1. Physical output per man-hour in the private economy (not including the government sector) has grown at an average rate that appears to be about 2.4 percent per annum.

2. Comparing that output with a modified measure of labor input--one in which a man-hour of highly paid work, such as that of a specialized craftsman or scientist, counts for proportionately more than a man-hour of low wage labor--yields a measure of productivity for the private economy that grew at about 2.0 percent per annum.

3. A measure of productivity for the private economy that compares output not only with labor inputs but also with tangible capital, each factor weighted respectively by its market share, grew at about 1.7 percent per annum.

4. All of the foregoing indexes of productivity in the private economy rose somewhat more rapidly than the corresponding indexes for the economy as a whole including the government sector--which rose only about 1.5 percent per annum. [5]

1/ John W. Kendrick, Productivity Trends in the United States (Princeton, N. J.: Princeton University Press, 1961).

2/ Moses Abramowitz, "Resource and Output Trends in the United States since 1870," American Economic Review, May 1956.

3/ W. E. G. Salter, Productivity and Technical Change (Cambridge, England: Cambridge University Press, 1960).

4/ Solomon Fabricant, "Basic Facts on Productivity Change," Occasional Paper No. 63 (New York: National Bureau of Economic Research, 1959) also published in slightly condensed form in Kendrick, op. cit.

5/ This is because, in the government sector, input and ouput are equated, leading to productivity equal to unity, which then pulls down productivity for the aggregate.

These productivity measures were obtained by studying the U. S. economy for the period 1889-1957, measured in terms of net national product. The aggregate output for the economy in the same period, also measured in net national product, rose at an average annual rate of 3.5 percent. Using the total factor inputs of paragraph 3 above, this would attribute approximately 50 percent of the growth in the U. S. economy over this time span to increases in productivity rather than increases in total factor input.

The great bulk of these increases in productivity have, of course, been enjoyed by consumers in the form of the goods and services for which they have worked and saved. Moreover, this expanded productivity, coupled with the fruits of a rising technology and material culture level, has produced not only a larger volume and a better quality of goods and services, but also many new or dramatically improved goods and services. Even more importantly from a welfare standpoint, these gains of productivity have been widely diffused, in the distributive sense. Also, real hourly earnings, including fringe benefits of many varieties, have grown about as rapidly as has output per man-hour. Together, then, the twin goals of diffusion and real income gains have been met, producing what can clearly be labeled an approximately equivalent rise in welfare, as defined in economic terms.

Other Factors Affecting Productivity Measures

Kendrick does raise a note of caution which must be borne in mind in interpreting productivity advances, however. It is that, although changes in total factor productivity can be initially linked to changes in production efficiency, the underlying changes in efficiency themselves may be a result of technological innovation, or changes in scale or output, or changes in the rate of utilization of capacity. Hence, mere description of the components of changing productive efficiency alone does not fully serve to separate the causes of those changes.

This can be illustrated in a number of ways:

* Changes in the absolute volume of output is a rough but useful general measure of an institution's success in exploiting its opportunities for technical innovations.

* However, the volume of technological innovation designed to reduce costs (thereby increasing productivity as measured by the "factor inputs" methodology described earlier) is substantially influenced by economic conditions at a particular point in time--which in turn introduces lags into the time series which are difficult to predict or correlate.

* Also, over the long run, technological progress depends on the quantity and quality of resources devoted to increasing scientific and technical knowledge and to developing commercial applications of this knowledge.

* As changes in scale occur, new opportunities for adapting technological improvements to products or processes may occur. And if industry continues to attempt to operate at the least cost or best-practice technique, then changes in techniques are almost certain to occur.

* Productivity increases, on the other hand, are often associated more directly with managerial alertness and flexibility in adapting the increased technical knowledge brought about through the innovative process.

Synthesis

What Kendrick is saying is that it is difficult to segregate the effects of increases in productivity or of changes in scale from pure advances in technology. Whether such segregation is, in fact, necessary, except to the purist, is debatable. In view of the circular nature of the innovative process, the question is not unlike that of the chicken and the egg. For our purposes here, it is simply sufficient to recognize that:

1. Technological progress, as measured by productivity indices, plays a major role in raising aggregate output and per capita output.

2. Changes in productivity have in recent periods been largely a result of changes in technology.

3. Increases in output may also be a result of changes in scale of operation. And while changes in scale do not automatically ensure that there will be economies of scale, changes in scale in stepping stone fashion provide the opportunities and incentives for technological changes which do, in turn, yield what are often superficially labeled as economies of scale.

4. Other influences--economic conditions, quality, and quantity of resources devoted to scientific and technical advance and application, entrepreneurial-managerial prowess, and the like--also have a major effect on the rate of changes in technology and output. Indeed, the role of management and entrepreneurship, in combination with the treble role of education--scientific/technical, entrepreneurial, and dissemination--may constitute a special "soft science" dimension of technology itself.

5. MEASURES OF TECHNOLOGICAL PROGRESS: SOME PRODUCTION FUNCTION RESULTS

Two Introductory Notes

Focus of Section. In this section, we review a sample of recent works in which the economic role of technological change has been quantified by use of production function derivations. Our aim is to illustrate the essence of the approach, to indicate some of the implicit assumptions, and to summarize the quantitative results obtained.

Concentration on Two Alternatives. There appear to be at least three alternative ways of measuring technical progress by use of a production function approach:

1. One may explicitly attempt to estimate separately all of the factors that contribute to economic growth.

2. One may measure the residual and then disaggregate it into its various components, one of which is technological progress.

3. One may measure the residual and label it technological progress in its entirety.

The first approach has been the one least attempted, largely because of the very great amount of data required, the potential problems of statistically spurious correlation which are implicit in separate measurement, and the necessarily arbitrary assumptions that must therefore be made.

Accordingly, we will confine our review to the second and third approaches--disaggregating the residual, and treating the residual as a whole.

Denison's Residual Disaggregation

Denison[1/] begins his work in much the same way as Kendrick,[2/] in that he computes productivity gains over the period 1909-1957 and then calculates an index of technological progress.[3/] Denison does not stop here, however. He proceeds to disaggregate the residual and explain the importance of its causal factors by dividing the residual among them. Table A-1 summarizes the process.

1/ Denison, op. cit.
2/ Kendrick, op. cit.
3/ However, in the strictest sense, Denison does not use a production function of quite the same general form used by other scholars reviewed in this section.

TABLE A-1

ALLOCATION OF GROWTH RATE OF REAL NATIONAL INCOME AMONG THE SOURCES OF GROWTH

	Percentage Points in Growth Rate	
	1909-29	1929-57
Real national income	2.82	2.93
Increase in total inputs	2.26	2.00
Labor input (adjusted for quality)	1.53	1.57
Employment	1.11	1.00
Hours	-0.23	-0.53
Effect of shorter hours on quality	0.23	0.33
Education	0.35	0.67
Increased experience and better use of women	0.06	0.11
Changes in age-sex composition of labor force	0.01	-0.01
Capital input	0.73	0.43
Nonfarm residential structures	0.13	0.05
Other structures and equipment	0.41	0.28
Inventories	0.16	0.08
United States-owned assets abroad	0.02	0.02
Foreign assets in United States	0.01	0.00
Increase in output per unit of input	0.56	0.93
Restrictions against optimum use of resources	n.a.	-0.07
Reduced waste in agriculture	n.a.	0.02
Industry shift from agriculture	n.a.	0.05
Advance in knowledge	n.a.	0.58
Change in lag in application of knowledge	n.a.	0.01
Economies of scale--independent growth of local markets	n.a.	0.07
Economies of scale--growth of national market	0.28	0.27

Source: Denison, op. cit., Table 32, p. 266.

Denison is careful to note that, in many of the areas into which he has delved, there are little or no data or previous research available. As a result his work is a monumental assembly of numbers, many of which he builds on the basis of educated guesses in order to derive even a useful approximation.

In analyzing Table A-1, it can be seen that the residual--Denison's "Increase in Output per Unit of Input"--accounted for approximately 20 percent of the growth in total income during the 1909-1929 period, and 32 percent during the 1929-1957 period. Clearly, the latter period has seen a significantly higher contribution to growth in the residual.1/

In summarizing his results for 1929-1957, Denison observes that

> . . .five sources contributed an amount equal to 101 percent of the growth rate, out of a total of 109 percent contributed by all sources making a positive contribution.2/ These were increased employment (34 percent); increased education (23); increased capital input (15); the advance of knowledge (20); economies of scale associated with the growth of the national market (9).

It is clear that the increases in employment and capital input, a total of 49 percent, fall outside the sphere of technological progress, as it is generally viewed. Of the remaining 52 percent, a distinction as to which can be identified as a component of technological progress becomes more difficult.

As we have seen, such secondary factors as increase in education, advance of knowledge, and economies of scale are not always properly separable in analysis nor discretely independent in a causal framework. Going even a step further back in the process, the advance of knowledge is not really independent of increased education, since the knowledge-education cycle is essentially circular. And, since knowledge may be a product of experience, an advance of knowledge may itself be a result of increasing scale of operations or activity and hence contribute to economies of scale and also--by virtue of the added knowledge or perspectives gained from the larger scale--precipitate still further advances in knowledge.

1/ Significantly, Kendrick similarly found productivity to be higher for the period following World War I.

2/ This is not faulty arithmetic; some sources added negative contributions to growth--that is, retarded it.

Accordingly, one is compelled to conclude that there is no single mathematically or scientifically "correct" answer to the matter of residual shares among causal factors. About all that can be said is that Denison's work confirms the general validity of the residual approach. Beyond that, the attempt to treat all the components of technological change as independent causes of growth, as Denison has done, is an exciting but not wholly satisfying approach.

Solow's Aggregation Approach

Robert Solow's work on "Technical Change and the Aggregate Production Function"1/ is possibly the most widely quoted, debated, criticized, and imitated analysis of the role of technological progress in growth of the U. S. economy.2/ His approach follows the third of the three methodologies sketched previously--a direct measurement of the residual, which is then defined as a whole to be "technological progress."

Solow's results are shown in Table A-2, which also incorporates corrections discovered by Hogan. The index of technological change rose from 1 in 1909 to 1.85 in 1949, an average growth rate of 1.56 percent, while private nonfarm output per man-hour rose at an average rate of 1.81 percent. Hence, technological progress accounted for some 86 percent of the growth, a value somewhat higher than Kendrick's and Denison's estimates--50 and 52 percent, respectively.

Massell's Variation

In an attempt to overcome criticisms of Solow's work, Massell 3/ limits the scope of his own analysis to the manufacturing sector, in hopes of finding better data. However, Massell's results are very similar to Solow's, in that his index rises from 1 in 1909 to 2.9 in 1955--a growth rate of 2.34 percent per year.

1/ Robert M. Solow, op. cit., The Review of Economics and Statistics.

2/ See for example, Warren Hogan, "Technical Progress and Production Functions," The Review of Economics and Statistics, 40 (November 1958), pp. 407-11; Benton Massell, "Capital Formation and Technical Change in U. S. Manufacturing," The Review of Economics and Statistics, 42 (May 1960), pp. 182-88; Benton Massell, "A Disaggregated View of Technical Change," Journal of Political Economics, LXIX (December 1961), pp. 547-57; and Lave, op. cit.

3/ B. Massell, "Capital Formation and Technical Change in U. S. Manufacturing," op. cit.

TABLE A-2

DATA FOR CALCULATION OF A(t)

r	Percent Labor Force Employed (1)	Capital Stock ($ million) (2)	Col. 1 x Col. 2 (3)	Share of Property In Income (4)	Private Nonfarm GNP Per Man-Hour (5)	Employed Capital Per Man-Hour (6)	$\Delta A/A$ (7)	A(t) (8)
9	91.1	146,142	133,135	0.335	$0.623	$2.06	-0.017	1.000
0	92.8	150,038	139,235	0.330	0.616	2.10	0.039	0.983
1	90.6	156,335	141,640	0.335	0.647	2.17	0.002	1.021
2	93.0	159,971	148,773	0.330	0.652	2.21	0.040	1.023
3	91.8	164,504	151,015	0.334	0.680	2.23	0.007	1.064
4	83.6	171,513	143,385	0.325	0.682	2.20	-0.028	1.071
5	84.5	175,371	148,188	0.344	0.669	2.26	0.034	1.041
6	93.7	178,351	167,115	0.358	0.700	2.34	-0.010	1.076
7	94.0	182,263	171,327	0.370	0.679	2.21	0.072	1.065
8	94.5	186,679	176,412	0.342	0.729	2.22	0.013	1.142
9	93.1	189,977	176,869	0.354	0.767	2.47	-0.076	1.157
20	92.8	194,802	180,776	0.319	0.721	2.58	0.072	1.069
21	76.9	201,491	154,947	0.369	0.770	2.55	0.032	1.146
22	81.7	204,324	166,933	0.339	0.788	2.49	0.011	1.183
23	92.1	209,964	193,377	0.337	0.809	2.61	0.016	1.196
24	88.0	222,113	195,460	0.330	0.836	2.74	0.032	1.215
25	91.1	231,772	211,198	0.336	0.872	2.81	-0.010	1.254
26	92.5	244,611	226,266	0.327	0.869	2.87	-0.005	1.241
27	90.0	259,142	233,228	0.323	0.871	2.93	-0.007	1.235
28	90.0	271,089	243,980	0.338	0.874	3.02	0.020	1.226
29	92.5	279,691	258,714	0.332	0.895	3.06	-0.043	1.251
30	88.1	289,291	254,865	0.347	0.880	3.30	0.024	1.197
31	78.2	289,056	226,042	0.325	0.904	3.33	0.023	1.226
32	67.9	282,731	191,974	0.397	0.879	3.28	0.011	1.198
33	66.5	270,676	180,000	0.362	0.869	3.10	0.072	1.211
34	70.9	262,370	186,020	0.355	0.921	3.00	0.039	1.298
35	73.0	257,810	188,201	0.351	0.943	2.87	0.059	1.349
36	77.3	254,875	197,018	0.357	0.982	2.72	-0.010	1.429
37	81.0	257,076	208,232	0.340	0.971	2.71	0.021	1.415
38	74.7	259,789	194,062	0.331	1.000	2.78	0.048	1.445
39	77.2	257,314	198,646	0.347	1.034	2.66	0.050	1.514
40	80.6	258,048	207,987	0.357	1.082	2.63	0.044	1.590
41	86.8	262,940	228,232	0.377	1.122	2.58	0.003	1.660
942	93.6	270,063	252,779	0.356	1.136	2.64	0.016	1.665
943	97.4	269,761	262,747	0.342	1.180	2.62	0.071	1.733
944	98.4	265,483	261,235	0.332	1.265	2.63	0.021	1.856
945	96.5	261,472	252,320	0.314	1.296	2.66	-0.044	1.895
946	94.8	258,051	244,632	0.312	1.215	2.50	-0.017	1.812
947	95.4	268,845	256,478	0.327	1.194	2.50	0.016	1.781
948	95.7	276,476	264,588	0.332	1.221	2.55	0.024	1.810
949	93.0	289,360	269,105	0.326	1.275	2.70	--	1.853

urce: Solow, *op. cit.*

The Jorgenson and Griliches Departure

Perhaps the most controversial study on technological growth as measured by the residual was published in 1967 by Jorgenson and Griliches, both econometricians of note.[1/] Primary reason for the controversy is that their value for the residual is at odds with virtually every other researcher's results to date.

According to Jorgenson and Griliches, over the period 1945-1965 the residual accounted for only some 2.8 percent of a total growth in output of 3.59 percent--a mere 0.1 percent point of the total. The remainder is held to have resulted from increases in inputs.

This is certainly at odds with the other results reviewed here, as well as many others we have not included.[2/] In fact, this divergence of results inspired the U. S. Office of Business Economics to commission Edward Denison to explore and comment on the work by Jorgenson and Griliches.[3/]

Jorgenson and Griliches set out to prove that the high residuals resulting from previous work were a result of errors that had been made in quantifying the inputs for labor and capital. Accordingly, the J & G model is

$$\sum_{i=1}^{m} q_i y_i = \sum_{j=1}^{n} p_j x_j \tag{3}$$

where: y_i = quantity of the ith output,

x_j = quantity of the jth input,

q_i = price of the ith output, and

p_j = price of the jth input.

1/ D. W. Jorgenson and Z. Griliches, "The Explanation of Productivity Change," The Survey of Current Business, May 1969.

2/ For a review of results prior to 1966, see Lave, op. cit.

3/ Edward Denison, "Some Major Issues in Productivity Analysis: An Examination of Estimates by Jorgenson and Griliches," The Survey of Current Business, May 1969.

They differentiate (3) to obtain

$$\sum w_i \left[\frac{\dot{q}}{q} + \frac{\dot{y}_i}{y_i}\right] = \sum v_j \left[\frac{\dot{p}_j}{p_j} + \frac{\dot{x}_j}{x_j}\right]$$

where: $w_i = \dfrac{q_i y_i}{\sum q_i y_i}$,

and: $v_j = \dfrac{p_j x_j}{\sum p_j x_j}$

which are the relative shares of the ith output within the total output and the jth input within the total input, respectively. Next, defining total productivity in terms of a Divisia index number, P, J & G develop an expression for the rate of growth of total factor productivity as

$$\frac{\dot{p}}{p} = \sum w_i \left(\frac{\dot{y}_i}{y_i}\right) - \sum v_j \left(\frac{\dot{x}_j}{x_j}\right) .$$

They further show that the growth rate of total factor productivity is zero if and only if the shift in the production function is zero. (A shift in the production function would mean that technological progress has occurred.)

Using the U. S. private domestic net product for output, plus a host of input series and weighting factors, they begin a sequential process of "eliminating errors" in previous research. The process consists of six steps, the results of which are shown in Table A-3, whereby the residual is sequentially reduced from 46 percent to a mere 2.8 percent of the growth of output.

Significantly, the initial estimate of productivity (46 percent) is essentially consistent with the findings of Kendrick and Denison. In the J & G process of "eliminating errors" of previous research, however, the contribution of the residual begins to diverge from commonly found results. However, in his analysis and critique of the J & G work for DBE, Denison analyzed these results in the light of his previous work and was able to attribute all but 0.33 percentage points of the difference between his residual and J & G's residual to differences in techniques or data.

TABLE A-3

TOTAL OUTPUT, INPUT, AND FACTOR PRODUCTIVITY, U. S. PRIVATE DOMESTIC ECONOMY, 1945-65
(Average Annual Rates of Growth)

	(1) Output	(2) Input	(3) Productivity	(4) (3/1)(100)
1. Initial estimates	3.49	1.83	1.60	46.0%
Estimates after correction for				
2. Errors of aggregation	3.39	1.84	1.49	44.0%
3. Errors in investment goods prices	3.59	2.12	1.41	41.5%
4. Errors in relative utilization	3.59	2.57	0.96	26.8%
5. Errors in aggregation of capital utilization	3.59	2.97	0.58	16.2%
6. Errors in aggregation of labor services	3.59	3.47	0.10	2.8%

Source: Jorgenson and Griliches, op. cit.

In analyzing the methodology used by Jorgenson and Griliches, as well as the critical review by Denison, we too conclude that the Jorgenson-Griliches methodology and assumptions err in two dimensions. First, they do not "correct" previous errors, but instead alter the assumptions. Second, they introduce new errors in conception. Their original results (the initial estimates shown in Table A-3), seem a reasonable and consistent assessment of the role of technological progress in economic growth. Their subsequent refinements, however, act to understate the contribution of the technological component through (a) erroneous assumptions; and (b) embodiment of much of the evidence of technological progress within the base data series used, so that their effects are prematurely subtracted.

Progress Toward Quantification

The review of approaches and progress toward quantifying the role of technological progress in economic growth which we have presented in this paper is intended solely as an illustrative overview of the current state of the art, and not an exhaustive treatment. Because of the importance and widespread interest in the topic, economic literature is understandably replete with variations on the major themes sketched here. Perhaps the cardinal point for our present purposes, then, is that the results of these variations are also largely in line with the main stream described here.

Mansfield has summarized the empirical progress on technological contribution in these words:

> Although the studies are useful, the results are extremely rough. Because of the complex interactions among the various factors that affect the economic development of a country it is difficult to estimate from historical statistics the precise effect of a nation's rate of technological change on its rate of economic growth. All that can safely be said is that the effect has been substantial.[1/]

One of the more frequently cited shortcomings of estimates developed by either a production function or a total factor productivity approach, of course, is that each misses those benefits of technological progress that cannot be measured within the limitations of the existing methodologies. At least some of the culturally important fruits of technological progress that materially affect our American life styles (e.g., new and improved final products) are not yet adequately reflected in either the economic residual or the productivity gains methodologies.

Simply, then, the present state of the art in economic measurement precludes comfortably precise estimates of all of the dimensions of technological progress and all of its total and component effects on economic growth.

Nevertheless, the results that have been obtained are far from discouraging. Indeed, use of fairly conventional applications of production theory alone have yielded insights into (a) the aggregate economic role of technological progress, (b) the relative importance of factor inputs, and (c) the genuine importance of inputs exogenous to capital and labor. And these would appear to suffice for our objectives here.

Moreover, results of other research--which we have described here in some detail for the specialist--support the findings of our research. The high frequency with which researchers--often using different methodologies--conclude that technological progress plays a major role in economic growth lends credibility to the research which depends on nonquantitative evidence to explain technology's role in the production process. These mutually supportive findings are difficult to dismiss as meaningless.

1/ Mansfield, *op. cit.*, p. 5.

APPENDIX B

CALCULATION OF A_t AND G_t

This appendix contains the data and indicates the calculations performed in developing:

1. A_t for the period 1949 through 1968

2. A_t for the period 1909 through 1968

3. G_t for the period 1949 through 1968

The following sections describe each of these.

1. A_t FOR 1949-68

Calculations of A_t are based on the methodology developed by Solow which has been previously described in Chapter VI and Appendix A. Table B-1 shows the data used in the calculations and the results. Columns 1, 2, 4, 5 and 6 are input data for the calculations and 3,7 and 8 are arrived at computationally.

The base data used in developing entries in the data columns and the computations used in each case are discussed below:

Col.1: Percent Labor Force Employed
1949 taken from Table A-2
Labor force is defined here as private, civilian. non-agricultural. The percentage employed was derived from Table B-2 and Table B-3. The calculations are self-explanatory.

Col.2: Capital Stock
Gross stocks for all industries (constant cost 2) taken directly from Survey of Current Business, Department of Commerce, April 1970, p. 23, Table 1-Constant Dollar Gross and Net Stocks, 1925-68.

Col. 3: Col. 2 X Col. 3

Col. 4: Share of Property in Income
Share of property in income was calculated as shown in Table B-4 with specific table and line references indicated at left.

Col. 5: Private nonfarm GNP per Man-Hour
Derived from private nonfarm GNP divided by man-hours in non-agricultural establishments as shown in Table B-5.

Col. 6: Employed Capital per Man-Hour
Calculated by dividing employed capital in Col. 3 by the man-hour series from Table C.

Col. 7: $\Delta A/A = \Delta 5/5 - 4(\Delta 6/6)$

Col. 8: $A(t+1) = A(t)[1 + \Delta A(t)/A(t)]$

2. A_t FOR 1909-1968

Table A-2 contains the series for A_t from 1909 through 1949. In that the calculations of A_t for 1949-1968 required new data series, we chose to set $A_{1949} = 1.0$ to initiate the calculations. It is then possible to adjust our series--which indicates progress since 1949--to a base of 1909 by normalizing our series with Solow's ending A_{1949} of 1.853 by multiplying each of our A_t in 1949-1968 by 1.853. Table B-6 shows the result of this calculation in the 1949 through 1968 time period.

3. G_t FOR 1949-1968

As described in Chapter VI.

$$G_t = Q_t - \frac{Q_t}{A_t}$$

where: Q_t = Observed output in year t and

A_t = Technology level in year t.

Table B-7 shows the data and calculated results with output taken at GNP deflated constant 1958 dollars in millions and with G_t calculated relative to 1949 technology.

TABLE B-1

DATA FOR CALCULATION OF A(t)

Year	Percent Labor Force Employed (1)	Capital Stock (1958 $ million) (2)	Col. 1 x Col. 2 (3)	Share of Property In Income (4)	Private Nonfarm GNP Per Man-Hour (5)	Employed Capital Per Man-Hour (6)	ΔA/A (7)	A(t) (8)
1949	93.0	434,200	403,806	0.313	$2.946	$4.469	0.060	1.000
1950	93.3	452,500	422,183	0.322	3.136	4.489	0.007	1.060
1951	95.8	471,700	451,889	0.318	3.168	4.527	0.001	1.067
1952	96.2	488,500	469,937	0.299	3.191	4.625	0.023	1.068
1953	96.3	506,500	487,760	0.287	3.278	4.693	0.008	1.093
1954	93.0	523,200	486,576	0.290	3.335	4.844	0.038	1.102
1955	94.4	544,000	513,536	0.301	3.477	4.900	-0.014	1.144
1956	94.8	566,900	537,421	0.291	3.446	4.986	0.006	1.128
1957	94.6	588,900	557,099	0.288	3.504	5.174	0.011	1.135
1958	91.5	604,100	552,752	0.287	3.572	5.324	0.027	1.147
1959	93.2	620,900	578,679	0.293	3.674	5.337	0.006	1.178
1960	93.1	640,200	596,026	0.286	3.712	5.427	0.017	1.185
1961	91.7	658,100	603,478	0.288	3.793	5.518	0.034	1.205
1962	93.1	678,600	631,777	0.293	3.945	5.606	0.018	1.246
1963	93.0	700,400	651,372	0.295	4.031	5.661	0.027	1.268
1964	93.6	727,100	680,566	0.297	4.162	5.767	0.013	1.302
1965	94.4	761,900	719,234	0.302	4.230	5.831	0.006	1.319
1966	95.3	802,900	765,164	0.302	4.276	5.924	0.012	1.327
1967	95.2	842,200	801,774	0.292	4.363	6.099	0.021	1.343
1968	95.5	881,900	842,215	0.290	4.488	6.256	--	1.371

TABLE B-2

PERCENT OF PRIVATE, CIVILIAN, NONAGRICULTURAL LABOR FORCE EMPLOYED
(000)

Year	(1) Nonagr. Employed	(2) Gov't Employed	(3) Col. 1 - 2	(4) Unemployed	(5) Col. 3 + 4	% Labor Force Emp. Col. 3 ÷ 5
1950	51,760	6,026	45,734	3,288	49,022	93.3
1951	53,239	6,389	46,850	2,055	48,905	95.8
1952	53,753	6,608	47,145	1,883	49,028	96.2
1953	54,922	6,645	48,277	1,834	50,111	96.3
1954	53,903	6,751	47,152	3,532	50,684	93.0
1955	54,724	6,914	47,810	2,852	50,662	94.4
1956	57,517	7,278	50,239	2,750	52,989	94.8
1957	58,123	7,616	50,507	2,859	53,366	94.6
1958	57,450	7,839	49,611	4,602	54,213	91.5
1959	59,065	8,083	50,982	3,740	54,722	93.2
1960	60,318	8,353	51,965	3,852	55,817	93.1
1961	60,546	8,594	51,952	4,714	56,666	91.7
1962	61,759	8,890	52,869	3,911	56,780	93.1
1963	63,076	9,226	53,850	4,070	57,920	93.0
1964	64,782	9,596	55,186	3,786	58,972	93.6
1965	66,726	10,074	56,652	3,366	60,018	94.4
1966	68,915	10,791	58,124	2,875	60,999	95.3
1967	70,527	11,398	59,129	2,975	62,104	95.2
1968	72,103	11,848	60,255	2,817	63,072	95.5
1969	74,296	12,226	62,070	2,831	64,901	95.6

Source: Cols. 1 and 4: Employment and Earnings, Bureau of Labor Statistics, Vol. 16, No. 11, May 1970, p. 23.

Col. 2: See Table B-3.

TABLE B-3

CIVILIAN GOVERNMENT EMPLOYEES
(000)

Year	Federal	State and Local	Total
1950	1,928	4,098	6,026
1951	2,302	4,087	6,389
1952	2,420	4,188	6,608
1953	2,305	4,340	6,645
1954	2,188	4,563	6,751
1955	2,187	4,727	6,914
1956	2,209	5,069	7,278
1957	2,217	5,399	7,616
1958	2,191	5,648	7,839
1959	2,233	5,850	8,083
1960	2,270	6,083	8,353
1961	2,279	6,315	8,594
1962	2,340	6,550	8,890
1963	2,358	6,868	9,226
1964	2,348	7,248	9,596
1965	2,378	7,696	10,074
1966	2,564	8,227	10,791
1967	2,719	8,679	11,398
1968	2,739	9,109	11,848
1969	2,757	9,469	12,226

Source: Employment and Earnings, Bureau of Labor Statistics, Vol. 16, No. 11, May 1970, p. 51.

SHARE OF PROPERTY IN INCOME

Table/ Line	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958
1.10, line 1										
National Income	217,494	241,074	277,978	291,380	304,734	303,138	331,018	350,799	366,096	367,762
1.9, line 2										
Cap. Consump. Allow.	16,550	18,342	21,195	23,192	25,673	28,234	31,474	34,071	37,089	38,938
Total Income	234,044	259,416	299,173	314,572	330,407	331,372	362,492	384,870	403,185	406,700
1.10, line 2										
Compensation of Employees	141,029	154,471	180,687	195,308	209,111	207,956	224,479	243,058	255,996	257,816
1.10, line 17										
Rental, Inc., of Persons	8,438	9,361	10,321	11,500	12,677	13,598	13,898	14,313	14,811	15,418
1.10, line 13										
(1/2) Bus. and Prof. Prop., Inc.	11,313	11,989	13,063	13,563	13,732	13,779	15,142	15,670	16,390	16,587
Labor's Income	160,780	175,921	204,071	220,371	235,520	235,333	253,519	273,041	287,197	289,821
Labor's Share = $\frac{\text{line 9}}{\text{line 4}}$	0.687	0.678	0.682	0.701	0.713	0.710	0.699	0.709	0.712	0.713
Capital's Share 1. - line 11	0.313	0.322	0.318	0.299	0.287	0.290	0.301	0.291	0.288	0.287

Table/ Line	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
1.10, line 1										
National Income	400,025	414,522	427,341	457,687	481,927	517,281	559,020	620,760	654,000	714,400
1.9, line 2										
Cap. Consump. Allow.	41,378	43,408	45,244	49,970	52,601	56,048	59,589	64,093	68,600	73,300
Total Income	441,403	457,930	472,585	507,657	534,528	573,329	618,609	684,853	722,600	787,700
1.10, line 2										
Compensation of Employees	279,093	294,226	302,638	323,632	341,004	365,657	392,930	435,611	467,400	513,600
1.10, line 17										
Rental, Inc., of Persons	15,596	15,822	15,964	16,691	17,139	17,665	18,334	19,793	20,800	21,200
1.10, line 13										
(1/2) Bus. and Prof. Prop., Inc.	17,565	17,122	17,793	18,547	18,955	19,942	20,327	22,388	23,600	24,600
Labor's Income	312,254	327,170	336,395	358,870	377,098	403,264	431,591	477,792	511,800	559,400
Labor's Share = $\frac{\text{line 25}}{\text{line 20}}$	0.707	0.714	0.712	0.707	0.705	0.703	0.698	0.698	0.708	0.710
Capital's Share = 1. - line 27	0.293	0.286	0.288	0.293	0.295	0.297	0.302	0.302	0.292	0.290

Source: National Income and Product Accounts of U. S. (1946-1965), Department of Commerce, Tables 1.9 and 1.10.

TABLE B-5

PRIVATE NONFARM GNP PER MAN-HOUR

Year	Priv. Nonfarm GNP (billions) (1958 $)	Man-Hours in Nonagr. Estab. (billions)	GNP Per Man-Hour 3 ÷ 5
1949	266.2	90.36	2.946
1950	294.9	94.05	3.136
1951	316.2	99.82	3.168
1952	324.2	101.61	3.191
1953	340.7	103.94	3.278
1954	335.0	100.45	3.335
1955	364.4	104.81	3.477
1956	371.4	107.79	3.446
1957	377.2	107.66	3.504
1958	370.9	103.83	3.572
1959	398.3	108.42	3.674
1960	407.6	109.82	3.712
1961	414.8	109.36	3.793
1962	444.6	112.70	3.945
1963	463.8	115.06	4.031
1964	491.2	118.02	4.162
1965	521.7	123.34	4.230
1966	552.3	129.17	4.276
1967	573.5	131.45	4.363
1968	604.2	134.62	4.488

Source: National Income and Products Accounts of U. S., Department of Commerce, Table 1.8, line 4.

Business Conditions Digest, Department of Commerce, February 1970, Table 48, p. 108.

TABLE B-6

A_t FOR 1949-1968 RELATIVE TO 1909 TECHNOLOGY

Year	A_t (1949 Base)	A_t (1909 Base)
1949	1.000	1.853
1950	1.060	1.964
1951	1.067	1.977
1952	1.068	1.979
1953	1.093	2.025
1954	1.102	2.042
1955	1.144	2.120
1956	1.128	2.090
1957	1.135	2.103
1958	1.147	2.125
1959	1.178	2.183
1960	1.185	2.196
1961	1.205	2.233
1962	1.246	2.309
1963	1.268	2.350
1964	1.302	2.413
1965	1.319	2.444
1966	1.327	2.459
1967	1.343	2.489
1968	1.371	2.540

TABLE B-7

CALCULATION OF G_t
(1949 Base Technology)

Year	Output (millions)	A_t	Output / A_t	G_t (millions)
1949	266,200	1.000	266,200	-
1950	294,900	1.060	278,208	16,692
1951	316,200	1.067	296,345	19,855
1952	324,200	1.068	303,558	20,642
1953	340,700	1.093	311,711	28,989
1954	335,000	1.102	303,993	31,007
1955	364,400	1.144	318,531	45,869
1956	371,400	1.128	329,255	42,145
1957	377,200	1.135	332,335	44,865
1958	370,900	1.147	323,365	47,535
1959	398,300	1.178	338,115	60,185
1960	407,600	1.185	343,966	63,634
1961	414,800	1.205	344,232	70,568
1962	444,600	1.246	356,822	87,778
1963	463,800	1.268	365,773	98,027
1964	491,200	1.302	377,266	113,934
1965	521,700	1.319	395,527	126,173
1966	552,300	1.327	416,202	136,098
1967	573,500	1.343	427,029	146,471
1968	604,200	1.371	440,700	163,500
Totals	8,233,100		6,869,133	1,363,967

APPENDIX C

ADJUSTMENTS TO G_t

As discussed in Chapter VII, the determinants of G_t found to have a significant effect on G_t during the 1949-1968 time frame were:

1) Sex-mix changes in the work force

2) Education of the work force

3) Research and development

Tables 5 and 7 of Chapter VII indicate the index values of labor quality changes as a result of these determinants.

In that both factors are related to the quality of the work force and therefore reflect productivity measures relative to the 1949 level, it is easy to adjust the data in Table B-1, Columns 5 and 6 to reflect labor quality changes.

The procedure is as follows:

1) To adjust for sex-mix changes, divide "GNP per man-hour" and "capital per man-hour" by the corresponding year's index value.

2) Recalculate A_t. The new A_t will reflect the applied technology level without the effect of sex-mix changes.

3) Recalculate G_t. These are the gains due to the remaining determinants of technological progress.

4) Calculate the difference between the original G_t and the new G_t. This difference represents the contribution to G_t from sex-mix changes.

5) Multiply the indexes for sex-mix changes and education for corresponding years.

6) Repeat steps 1 through 4. The result yields the combined effects of sex-mix changes and education. Tables C-1 and C-2 show the results of the various computations for sex-mix changes and education, respectively.

TABLE C-1

SEX-MIX CHANGES

Year	(1) Q*	(2) A_t	(3) $\frac{Q}{A}$	(4) G_t $Q - \frac{Q}{A}$	(5) G_t For All DET	(6) G_t Due To Sex-Mix Changes 5-4
1949	266.2	1.0	266.2	0	0	0
1950	294.9	1.05877	278.53	16.369	16.692	0.323
1951	316.2	1.06613	296.59	19.613	19.855	0.242
1952	324.2	1.06614	304.09	20.112	20.642	0.530
1953	340.7	1.08934	312.76	27.942	28.989	1.047
1954	335.0	1.0977	305.18	29.816	31.007	1.191
1955	364.4	1.13839	320.10	44.299	45.869	1.570
1956	371.4	1.1217	331.10	40.300	42.145	1.845
1957	377.2	1.12788	334.43	42.767	44.865	2.098
1958	370.9	1.1397	325.44	45.463	47.535	2.072
1959	393.3	1.16977	340.49	57.806	60.185	2.379
1960	407.6	1.17524	346.82	60.777	63.634	2.857
1961	414.8	1.19398	347.41	67.391	70.568	3.178
1962	444.6	1.23379	360.35	84.247	87.778	3.531
1963	463.8	1.25576	369.34	94.462	98.027	3.565
1964	491.2	1.28763	381.48	109.724	113.934	4.210
1965	521.7	1.30325	400.31	121.393	126.173	4.780
1966	552.3	1.3102	421.54	130.761	136.098	5.337
1967	573.5	1.32409	433.128	140.372	146.471	6.099
1968	604.2	1.35037	447.433	156.767	163.500	6.732

* All $'s in billions of 1958 constant $'s.

TABLE C-2

SEX-MIX AND EDUCATION CHANGES

Year	(1) Q*	(2) A_t	(3) $\frac{Q}{A}$	(4) G_t $Q - \frac{Q}{A}$	(5) G_t For All DET	(6) G_t Due To Sex-Mix And Education
1949	266.2	1.0	266.2	0	0	0
1950	294.9	1.05247	280.2	14.702	16.692	1.990
1951	316.2	1.05279	300.3	15.855	19.855	4.000
1952	324.2	1.04577	310.0	14.189	20.642	6.453
1953	340.7	1.06163	320.9	19.778	28.989	9.211
1954	335.0	1.0626	315.3	19.700	31.007	11.307
1955	364.4	1.09447	332.9	31.453	45.869	14.416
1956	371.4	1.06663	348.2	23.200	42.145	18.945
1957	377.2	1.06906	352.8	24.367	44.865	20.498
1958	370.9	1.0733	345.6	25.330	47.535	22.205
1959	398.3	1.09424	364.0	34.300	60.185	25.885
1960	407.6	1.09169	373.4	34.234	63.634	29.400
1961	414.8	1.10226	376.3	38.482	70.568	32.086
1962	444.6	1.13237	392.6	51.972	87.778	35.806
1963	463.8	1.14493	405.1	58.710	98.027	39.317
1964	491.2	1.16717	420.8	70.353	113.934	43.581
1965	521.7	1.17441	444.2	77.477	126.173	48.696
1966	552.3	1.17293	470.9	81.428	136.098	54.670
1967	573.5	1.17785	486.9	86.596	146.471	59.875
1968	604.2	1.19436	505.9	98.322	163.500	65.178
Total					1,363.967	543.519

* All $'s in billions of 1958 constant $'s.

APPENDIX D

G(R&D) GENERATION PATTERN

In order to quantitatively describe the G(R&D) generation pattern, it is necessary to combine two assumptions made--the initial G(R&D) distribution and the lifetime distribution. Both of these distributions were assumed to be Poisson. The initial G(R&D) distribution has a mean of 3 years whereas the lifetime distribution has a mean of 4 years.

To combine these distributions, we assume that the occurrence of initial G(R&D) is independent of the lifetime of the G(R&D) stream ensuing from a particular R&D activity. Making this assumption of independence allows one to combine the distributions additively. From a theoretical standpoint, the sum of two independent Poisson distributions with means μ_1 and μ_2 is a Poisson distribution with mean $\mu_1 + \mu_2$. In this case, this would indicate that the G(R&D) generation pattern is a Poisson distribution with a mean of 7 years. Our actual G(R&D) generation pattern is a close approximation to this theoretical distribution.

The G(R&D) generation pattern departs from the theoretical distribution because we have truncated both the initial G(R&D) distribution and the lifetime distribution to something less than the maximum values. The G(R&D) generation pattern was, therefore, developed by the process of convoluting the two distributions. The process can be described as follows:

Defining p_k = the probability the G(R&D) will be occurring in year k after R&D performance,

α_i = the probability that initial G(R&D) occurs in year i after R&D and

β_j = the probability that the lifetime of a G(R&D) stream is j years,

Then $p_k = \sum_i \sum_j \alpha_i \beta_j$ for all $i + j = k$ and $k = 0, \ldots, n$.

The p_k's are then the yearly probabilities that G(R&D) is being generated by some R&D activity. Table 14 in Chapter VIII indicates the yearly probabilities for each year from 0--the current year--through the 18th year.

APPENDIX E

REGRESSION ANALYSIS

The functional relationship between past R&D and G(R&D)--in a time series relationship--was determined by least-squares regression. Data requirements consisted of R&D performance and G(R&D). The series for G(R&D) developed in Chapter VII and shown in Table 10 served as input data for the regression. Data used for R&D performance are discussed below.

THE R&D SERIES

In order to obtain a sufficiently long series for total U.S. R&D performance, it was necessary to utilize a multitude of sources. Table E-1 contains the series (current dollars and GNP deflated) used in the computations. Sources for specific current dollars annual figures are discussed below:

1937-1938

Taken from U.S. Department of Commerce, Long Term Economic Growth 1860-1965, Bureau of the Census; October, 1966; pp. 198-99, Cols. B-52 and B-53, and increased by 16 percent for greater conformance to more recent trends.

1939

Interpolated between 1938 and 1940 data.

1940-1948

Taken directly from source cited for 1937-1938 data above.

1949-1950

Taken from Raymond H. Ewell, "Role of Research in Economic Growth," Chemical and Engineering News, Vol. 33, No. 29 (July 18, 1955).

1951

Taken from Leonard H. Silk, The Research Revolution, McGraw-Hill Publishing Company, New York, 1960.

1952

Taken from reference cited for 1949-1950 data.

1953-1968

Taken directly from National Patterns of R&D Resources, 1953-1970, National Science Foundation, NSF 69-30, September 1969.

The above base figures are also shown as deflated by the GNP deflator to 1958 dollars.

WEIGHTED R&D SERIES

Utilizing the G(R&D) generation pattern weights as shown in Table 14, Chapter VIII, the deflated R&D series can be used to determine the sum of past R&D expenditures for any year for which 18 past data points are available. Because the R&D series begins in 1937, the first year available for use is 1955. Table E-2 contains the series for R_t for t from 1955 through 1968.

REGRESSION ANALYSIS

The 14 data pairs available (1955-1968) were then analyzed to ascertain the parameters for the hypothesized linear model relating $G(R\&D)_t$ and R_t developed in Chapter VIII. The results obtained indicate a close relationship of the data to the hypothesis. Specifically, the results were that

$$G(R\&D) = -4954.15 + 7.23217\ R_t\ .$$

The coefficient of determination was 0.970161, the highest of any forms that were empirically estimated.

TABLE E-1

TOTAL U. S. R&D
($ millions)

Year	Current $*	1958 $ GNP Deflated
1937	261	586.5
1938	305	694.8
1939	330	763.9
1940	345	785.9
1941	900	1,906.8
1942	1,072	2,022.6
1943	1,210	2,130.3
1944	1,380	2,371.1
1945	1,520	2,546.1
1946	1,780	2,668.7
1947	2,260	3,029.5
1948	2,610	3,278.9
1949	2,800	3,539.8
1950	3,360	4,189.5
1951	4,000	4,672.9
1952	4,500	5,142.9
1953	5,207	5,896.9
1954	5,738	6,404.0
1955	6,279	6,907.6
1956	8,483	9,024.5
1957	9,912	10,166.2
1958	10,870	10,870.0
1959	12,540	12,342.5
1960	13,730	13,291.4
1961	14,552	13,912.0
1962	15,665	14,806.2
1963	17,371	16,204.3
1964	19,215	17,644.6
1965	20,449	18,439.1
1966	22,285	19,565.4
1967	23,680	20,136.1
1968	25,330	20,711.4

* See text for source.

TABLE E-2

WEIGHTED R&D

Year	R_t*
1955	3,455.86
1956	3,847.03
1957	4,295.20
1958	4,812.02
1959	5,415.90
1960	6,124.72
1961	6,944.93
1962	7,864.75
1963	8,855.92
1964	9,883.76
1965	10,920.50
1966	11,954.40
1967	12,987.70
1968	14,026.10

* In millions of 1958 constant $'s.

APPENDIX F

RATE OF RETURN CALCULATION

The simplest methodology for calculating a rate of return on an investment is illustrated below:

$$\% \text{ Rate of return on investment} = \frac{\text{Net Income}}{\text{Investment}} \times 100\% \qquad (1)$$

If income occurs over more than 1 year, the rate can be divided by the time span to obtain the average annual rate of return.

In our case, the $7.23 return minus $1.00 investment yields a net income of $6.23 over an 18-year period. Using (1) above,

$$\% \text{ Rate of return} = \frac{6.23\ (100)}{1.00} = 623\% \text{ or}$$

$$\text{Annual } \% \text{ rate of return} = \frac{623}{18} = 34.6\% .$$

Using (1), however, implicitly assumes a uniform series of discounted net income. This is clearly not the case with the G(R&D) generation pattern due to its bell-shaped characteristics. To accurately calculate the annual rate of return, a more elaborate technique is required.

The methodology used to calculate an exact rate of return is based on an iterative procedure in which successive "interest" percentages are used to calculate the "present worth" of the stream of net cash flows. The correct "rate of return" is that which causes the "present worth" of negative flows to exactly equal the "present worth" of positive flows. We applied the series of net cash flows resulting from the NASA 1959-1969 R&D expenditure series (in 1958 millions $) in calculating the exact rate of return. Since the iterative procedure is a time consuming process, we utilized a computer to perform the calculations. Table F-1 shows the results of the calculations with an annual rate of return of 33.1829 percent.

ANALYSIS OF NET G(R&D) CASH FLOW SERIES ARISING FROM
NASA R&D EXPENDITURES* WITH 33.1829% RATE OF RETURN

Year	This Period's Net Flow	Cumulative Flow End of Period	Present Worth This Period's Net Flow	Cumulative Present Worth End of Period
1959	-127	-127	-127	-127
1960	-343	-470	-246.14	-373.14
1961	-561	-1,031	-288.895	-662.035
1962	-1,120	-2,151	-413.889	-1,075.92
1963	-2,058	-4,209	-545.757	-1,621.68
1964	-2,400	-6,609	-456.724	-2,078.4
1965	-2,073	-8,682	-283.094	-2,361.5
1966	-709	-9,391	-69.4809	-2,430.98
1967	2,626	-6,765	184.673	-2,246.31
1968	6,134	-631	309.557	-1,936.75
1969	10,380	9,749	375.909	-1,560.84
1970	16,462	26,211	427.815	-1,133.03
1971	19,311	45,522	360.136	-772.89
1972	20,864	66,386	279.221	-493.669
1973	20,764	87,150	199.411	-294.258
1974	19,016	106,166	131.053	-163.205
1975	16,010	122,176	79.1785	-84.0267
1976	12,384	134,560	43.9506	-40.076
1977	8,797	143,357	22.4041	-17.6719
1978	5,737	149,094	10.4849	-7.18697
1979	3,430	152,524	4.49846	-2.68851
1980	1,878	154,402	1.76748	-0.921029
1981	939	155,341	0.63418	-0.286849
1982	426	155,767	0.206464	-0.080385
1983	174	155,941	0.060516	-0.019868
1984	63	156,004	0.015723	-0.004144
1985	19	156,023	0.003402	-0.000742
1986	5	156,028	0.000642	-0.000099
1987	1	156,029	0.000092	0

* All in 1958 $ millions.

APPENDIX G

MANUFACTURING INDUSTRY LEVEL TECHNOLOGICAL PROGRESS

As discussed in Chapter IX, the Solow model was applied to the 2-digit manufacturing industries to yield some insight into the rate of technological progress at this level. Ultimately, the industry level comparisons yield indications that the mix of activities among the industries can influence the actual gains in output due to technological progress to the U. S. economy. This is due to the dramatically different rates of technological progress between industries.

The methodology used was identical to that used for the private, nonfarm sector. Data requirements and availability were, however, different. As might be anticipated, the most difficult data to obtain at the industry level was capital stock and output. Some assumptions and interpolations were required to obtain series long enough to permit analysis.

Tables G-1 through G-20 include the same data for all manufactures and 2-digit manufacturing industries as Table B-1 for the private, nonfarm sector except that the data sources were of necessity different. Sources and treatment of the basic data used to analyze the industry level technological progress are discussed below.

Capital stock adjustment (CAP ADJ)--This column is identical to Column 1, Table B-1. It reflects the percent employed for the private, nonfarm sector and is used to adjust capital stock in existence to reflect "utilized capital stock." Ideally, this should vary by industry but is not available at that level. Implicitly, then nonutilization of capital is considered to be at the same level for each industry.

CAPITAL STOCK--The basic data series for capital stock for all manufactures at the 2-digit level was obtained from Robert C. Wasson, John C. Musgrave and Claudia Harkins, "Alternative Estimates of Fixed Business Capital in the United States, 1925-1968," Survey of Current Business, April, 1970. Gross stocks, constant cost 2, for all manufacturing were taken directly from Table 1 of the referenced study. This series was used directly for all manufactures. The 2-digit industry level capital stock was derived from this series by apportioning to the industry level based on its percentage of total book value of depreciable assets in manufacturing. The latter was obtained from the Census of Manufactures for 1957 and 1963. Annual percentages were estimated from these two points assuming a linear function. Individual industry percentages were then summed and normalized to 100 percent.

Employed Capital (EMPLOYED CAP)--This column is obtained by multiplying capital stock by the adjustment factor to reflect utilized capital.

Capital's share in income (CAP SHARE)--Labor's share in income was first calculated by developing the ratio of labor payments to income. Specifically, payroll for all employees was divided by value added to determine labor's share of income. Capital's share of income was then calculated as one minus labor's share. The data were taken from Census data for available years and Survey of Manufactures data were used to fill in between the Census years.

Output per man-hour (OUTPUT/HOUR)--Output was taken as "value added" and labor hours were a combination of "production workers" hours and an adjustment to reflect nonproduction worker hours. Production hours were multiplied by the ratio of total employees to production employees since labor hours are only available for production employees.

Employed capital per man-hour (CAP/HOUR)--Labor hours calculated above were utilized to divide employed capital as previously described.

The remaining two columns were calculated as has been previously described.

TABLE G-1

99 ALL MANUFACTURES

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	104700000	97371000	.4496	3.5539	3.6319	.0988	1.0000
1950	.933	108200000	100950600	.4804	3.8645	3.4890	-.0174	1.0988
1951	.956	113890000	109020400	.4515	3.7821	3.4574	.0058	1.0797
1952	.962	119100000	114574200	.4408	3.8566	3.5641	.0505	1.0859
1953	.963	124100000	119508300	.4362	4.0208	3.4876	.0045	1.1408
1954	.930	129300000	120249000	.4612	4.2378	3.9054	.0450	1.1460
1955	.944	134300000	126779200	.4746	4.4165	3.8676	.0302	1.1975
1956	.948	141200000	133857600	.4891	4.6471	4.0325	-.0337	1.2337
1957	.946	147900000	139913400	.4716	4.6240	4.2841	-.0145	1.1921
1958	.915	151600000	138714000	.4781	4.7212	4.6283	.0618	1.1748
1959	.932	154000000	143528000	.4959	4.9515	4.4850	-.0116	1.2474
1960	.931	157200000	146353200	.4882	4.9451	4.5801	.0052	1.2329
1961	.917	160300000	146995100	.4905	5.0486	4.7281	.0391	1.2394
1962	.931	163300000	152032300	.4989	5.2385	4.7007	.0423	1.2879
1963	.930	165700000	155031000	.5144	5.5089	4.7659	.0218	1.3423
1964	.936	171500000	160524000	.5311	5.6428	4.7839	.0299	1.3715
1965	.944	179000000	168976000	.5338	5.8590	4.8483	.0146	1.4125
1966	.953	189000000	180117000	.5330	5.9595	4.8690	-.0443	1.4331
1967	.952	198100000	188591200	.4921	5.7060	4.8680	*.0000	1.3696

TABLE G-2

20 FOOD AND KINDRED PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	11441092	10640216	.5546	3.6477	3.5247	.0393	1.0000
1950	.933	11781898	10992511	.5630	3.8419	3.5979	-.0706	1.0393
1951	.958	12347869	11829259	.5445	3.7440	3.9061	.0296	.9659
1952	.962	12877092	12387763	.5505	3.9435	4.0623	.0443	.9946
1953	.963	13369913	12875227	.5588	4.2833	4.3380	.0613	1.0387
1954	.930	13889355	12908730	.5372	4.2430	3.8504	.0274	1.1023
1955	.944	14365399	13560937	.5444	4.3682	3.8595	.0300	1.1325
1956	.948	15049096	14266543	.5470	4.6572	4.1013	-.0035	1.1664
1957	.945	15706240	14858104	.5542	4.7782	4.3293	.0784	1.1624
1958	.915	16040796	14677328	.5691	5.1371	4.2634	.0348	1.2535
1959	.932	16235450	15131439	.5782	5.3771	4.3380	.0256	1.2972
1960	.931	16512288	15372940	.5794	5.5715	4.4088	.0177	1.3305
1961	.917	16776196	15383772	.5842	5.6969	4.4420	.0138	1.3540
1962	.931	17027291	15852408	.5881	5.9100	4.6180	.0352	1.3726
1963	.930	17317629	16105395	.6043	6.2950	4.8310	.0180	1.4210
1964	.936	17750250	16614234	.6084	6.4424	4.8705	-.0227	1.4465
1965	.944	18457585	17423960	.6099	6.5800	5.2464	-.0099	1.4137
1966	.953	19415970	18503419	.6167	6.7180	5.5223	.0134	1.3997
1967	.952	20274544	19301366	.6201	7.0089	5.7856	*.0000	1.4185

TABLE G-3

21 TOBACCO MANUFACTURES

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	304677	283350	.7331	4.8196	1.5015	.0050	1.0000
1950	.933	324167	302448	.7363	5.3775	1.7351	-.0997	1.0050
1951	.958	350732	336001	.7312	5.1932	1.9009	-.0534	.9048
1952	.962	377309	362971	.7225	5.1841	2.0452	.0722	.8565
1953	.963	403821	388880	.7433	5.7944	2.1436	-.0199	.9184
1954	.930	431862	401632	.7368	5.9066	2.2618	.0307	.9001
1955	.944	460112	434346	.7488	6.3804	2.4040	.0256	.9277
1956	.948	495894	470108	.7626	7.2660	2.7588	-.0224	.9515
1957	.946	532144	503408	.7696	7.6631	3.0562	.0972	.9301
1958	.915	558494	511022	.7915	8.6868	3.1406	.0000	1.0205
1959	.932	580580	541101	.7899	9.0129	3.2909	.0019	1.0206
1960	.931	606163	564338	.7933	9.5103	3.5154	.0090	1.0224
1961	.917	631903	579455	.7966	10.1218	3.7590	-.0177	1.0317
1962	.931	657772	612386	.7962	10.3901	3.9764	-.0144	1.0134
1963	.930	685804	637798	.8033	10.8538	4.2839	-.0083	.9988
1964	.936	720300	674201	.8009	10.8838	4.3436	-.0539	.9905
1965	.944	767194	724231	.8004	11.6428	5.1023	-.0341	.9371
1966	.953	826308	787472	.8097	12.2592	5.7036	-.0083	.9051
1967	.952	883130	840740	.8125	12.3717	5.8291	*.0000	.8976

TABLE G-4

22 TEXTILE MILL PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	5715573	5315483	.3728	2.4359	2.3378	.1012	1.0000
1950	.933	5779313	5391166	.4035	2.6210	2.1607	-.1028	1.1012
1951	.958	5942408	5692827	.3658	2.4755	2.4256	-.0183	.9880
1952	.962	6077911	5846951	.3641	2.4976	2.6198	.0134	.9699
1953	.963	6185889	5957011	.3615	2.5296	2.6146	-.0399	.9829
1954	.930	6291738	5851316	.3615	2.5284	2.9346	.0681	.9437
1955	.944	6375758	6018716	.3875	2.6859	2.8598	-.0093	1.0079
1956	.948	6535866	6196001	.3781	2.7121	3.0072	-.0149	.9985
1957	.946	6670586	6310374	.3855	2.7587	3.2830	-.0138	.9837
1958	.915	6657666	6091764	.3952	2.7847	3.4921	.0959	.9701
1959	.932	6580420	6132951	.4216	2.9868	3.2595	.0201	1.0631
1960	.931	6530717	6080097	.4271	3.1045	3.4029	.0233	1.0846
1961	.917	6469387	5932428	.4353	3.1855	3.4201	.0549	1.1098
1962	.931	6396788	5955409	.4502	3.3400	3.3533	.0069	1.1708
1963	.930	6332266	5889008	.4472	3.3721	3.3730	.0522	1.1788
1964	.936	6311200	5907283	.4534	3.4918	3.2431	.0684	1.2403
1965	.944	6374906	6017911	.4756	3.7350	3.2202	.0065	1.3251
1966	.953	6506392	6201068	.4714	3.7502	3.2037	-.0162	1.3338
1967	.952	6585240	6269149	.4510	3.7439	3.3052	*.0000	1.3122

TABLE G-5

23 APPAREL AND RELATED PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	760645	707400	.3599	2.3772	.3391	-.0299	1.0000
1950	.933	810651	756524	.3379	2.3795	.3709	.0021	.9701
1951	.958	878877	841965	.3711	2.4697	.4129	-.0278	.9722
1952	.962	947083	911094	.3651	2.4437	.4330	.0545	.9451
1953	.963	1015262	977697	.3798	2.5039	.4415	-.0362	.9966
1954	.930	1087413	1011294	.3779	2.5867	.4788	.0025	.9605
1955	.944	1160218	1095246	.3773	2.6157	.4899	.0039	.9629
1956	.948	1252162	1187049	.3780	2.6872	.5213	-.0164	.9667
1957	.946	1345446	1272792	.3862	2.7279	.5683	.0158	.9508
1958	.915	1413822	1293647	.4027	2.8564	.6147	.0365	.9659
1959	.932	1471470	1371410	.4249	2.9475	.6062	-.0068	1.0012
1960	.931	1538045	1431920	.4272	3.0240	.6558	-.0043	.9943
1961	.917	1605084	1471862	.4228	3.0627	.6829	.0101	.9901
1962	.931	1672519	1557115	.4171	3.1263	.6998	.0409	1.0001
1963	.930	1745516	1623330	.4373	3.2604	.7002	-.0132	1.0410
1964	.936	1835050	1717607	.4262	3.2527	.7179	-.0240	1.0273
1965	.944	1956291	1846739	.4219	3.2581	.7639	-.0030	1.0026
1966	.953	2108862	2009745	.4328	3.3158	.8028	.0098	.9996
1967	.952	2255765	2147488	.4585	3.4523	.8620	*.0000	1.0094

TABLE G-6

24 LUMBER AND WOOD PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	3074515	2859299	.3775	2.2488	2.4437	.1978	1.0000
1950	.933	3137151	2926962	.4478	2.6192	2.1262	-.0062	1.1978
1951	.955	3257297	3120491	.4281	2.6471	2.2086	-.0324	1.1904
1952	.962	3364813	3236950	.3994	2.6327	2.3570	.0240	1.1518
1953	.963	3460032	3332011	.4039	2.7470	2.4658	-.0176	1.1795
1954	.930	3557043	3308050	.3934	2.7928	2.6923	.0818	1.1587
1955	.944	3644768	3440561	.4008	2.9923	2.5922	-.0405	1.2536
1956	.946	3779642	3583100	.3773	2.9320	2.7277	-.0910	1.2028
1957	.946	3904116	3693294	.3596	2.8004	3.0882	.0077	1.0933
1958	.915	3945542	3610171	.3746	2.8787	3.2649	.0943	1.1018
1959	.932	3950870	3682211	.4125	3.0961	3.0676	-.0613	1.2057
1960	.931	3974645	3700394	.3777	2.9661	3.2030	.0280	1.1318
1961	.917	3993554	3662089	.3880	3.1257	3.4107	.0497	1.1636
1962	.931	4007709	3731177	.4033	3.3022	3.4440	.0937	1.2214
1963	.930	4029306	3747254	.4183	3.6143	3.3821	.0637	1.3359
1964	.936	4081700	3820471	.4420	3.8696	3.4004	-.0101	1.4210
1965	.944	4193791	3958939	.4152	3.9646	3.4695	.0705	1.4067
1966	.953	4357962	4153138	.4380	4.2371	3.6214	-.0002	1.5058
1967	.952	4494295	4278569	.4283	4.3530	3.8577	*.0000	1.5055

TABLE G-7

25 FURNITURE AND FIXTURES

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	1127095	1048199	.3893	2.5748	1.6593	.0738	1.0000
1950	.933	1146271	1069471	.3924	2.6597	1.4982	.0123	1.0738
1951	.958	1186137	1136320	.4030	2,8034	1.6633	.0250	1.0870
1952	.962	1221013	1174615	.4104	2.9095	1.7120	.0346	1.1142
1953	.963	1251052	1204763	.3847	2.9616	1.6438	.0254	1.1527
1954	.930	1281363	1191668	.3911	3.1167	1.7550	.0710	1.1820
1955	.944	1307948	1234703	.4059	3.2787	1.6631	.0295	1.2660
1956	.948	1351002	1280750	.4223	3.3944	1.6819	-.0292	1.3034
1957	.946	1389816	1314766	.4195	3.3616	1.7631	-.0016	1.2653
1958	.915	1398662	1279775	.4090	3.4379	1.8693	.0281	1.2633
1959	.932	1394470	1299646	.4174	3.4171	1.7249	.0159	1.2988
1960	.931	1396565	1300202	.4158	3.4937	1.7504	.0138	1.3194
1961	.917	1396694	1280768	.4121	3.5951	1.8134	.0580	1.3376
1962	.931	1394909	1298660	.4235	3.7275	1.7195	.0725	1.4151
1963	.930	1395446	1297765	.4372	3.9935	1.6958	.0230	1.5178
1964	.936	1406300	1316297	.4284	4.0443	1.6563	.0838	1.5527
1965	.944	1437191	1356708	.4430	4.3895	1.6367	.0571	1.6828
1966	.953	1485162	1415359	.4516	4.6337	1.6207	-.0046	1.7788
1967	.952	1522795	1449701	.4501	4.6901	1.6826	*.0000	1.7707

TABLE G-8

26 PAPER AND ALLIED PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	6019203	5597859	.4888	3.4142	5.8908	.1322	1.0000
1950	.933	6319313	5895919	.5326	3.8664	5.7121	.0472	1.1322
1951	.953	6759388	6446872	.5640	4.1858	6.0421	-.1068	1.1857
1952	.962	7173631	6901033	.5169	3.9588	6.6227	.0652	1.0591
1953	.963	7588219	7307455	.5115	4.1449	6.3723	.0233	1.1282
1954	.930	8024358	7462653	.5160	4.3443	6.6665	.0494	1.1545
1955	.944	8457408	7983793	.5214	4.6137	6.7843	.0198	1.2115
1956	.948	9020986	8551894	.5228	4.8227	7.1047	-.0253	1.2356
1957	.946	9584216	9066668	.5155	4.8891	7.6756	-.0044	1.2043
1958	.915	9962546	9115729	.5129	4.9330	7.8788	.0690	1.1990
1959	.932	10261020	9563271	.5308	5.2753	7.8164	-.0084	1.2817
1960	.931	10617917	9885231	.5250	5.3413	8.1348	.0041	1.2709
1961	.917	10973817	10062991	.5227	5.4517	8.3937	.0131	1.2761
1962	.931	11328448	10546785	.5234	5.6033	8.6245	.0123	1.2927
1963	.930	11716676	10896509	.5256	5.7227	8.7688	.0103	1.3086
1964	.936	12210800	11429309	.5278	5.8656	9.0094	.0136	1.3221
1965	.944	12908406	12185535	.5396	6.1095	9.4829	.0152	1.3400
1966	.953	13802292	13153584	.5502	6.2830	9.7061	-.0263	1.3604
1967	.952	14647910	13944811	.5411	6.2908	10.2176	*.0000	1.3245

TABLE G-9

27 PRINTING AND PUBLISHING

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	3280774	3051120	.4110	3.2958	1.8735	.0169	1.0000
1950	.933	3419769	3190645	.4073	3.4050	1.9455	-.0131	1.0169
1951	.958	3627603	3475243	.4198	3.5078	2.1714	.0171	1.0036
1952	.962	3828827	3683331	.4227	3.6217	2.2484	.0851	1.0207
1953	.963	4023198	3874340	.4276	4.2313	2.6129	.0412	1.1076
1954	.930	4226817	3930940	.4214	4.3570	2.5397	.0439	1.1532
1955	.944	4426662	4178769	.4333	4.6142	2.6132	.0107	1.2038
1956	.948	4692358	4448356	.4427	4.7293	2.6979	-.0193	1.2167
1957	.946	4955094	4687519	.4432	4.7333	2.8269	.0213	1.1932
1958	.915	5120138	4684927	.4346	4.8742	2.8763	.0385	1.2186
1959	.932	5242930	4886411	.4475	5.0813	2.8917	.0335	1.2654
1960	.931	5394475	5022256	.4532	5.2330	2.8630	.0222	1.3078
1961	.917	5544296	5084120	.4535	5.3741	2.8886	.0242	1.3368
1962	.931	5692311	5299542	.4585	5.5958	2.9904	.0388	1.3692
1963	.930	5856004	5446084	.4736	5.9055	3.0822	.0231	1.4223
1964	.936	6071100	5682550	.4775	6.0445	3.0812	.0291	1.4552
1965	.944	6385109	6027543	.4811	6.3403	3.1988	.0549	1.4976
1966	.953	6793038	6473765	.4910	6.7716	3.2586	.0056	1.5797
1967	.952	7173795	6829453	.4846	6.8636	3.3115	*.0000	1.5885

TABLE G-10

28 CHEMICALS AND ALLIED PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	11819583	10992212	.6422	5.2546	8.5737	.1471	1.0000
1950	.933	12291953	11468392	.6764	6.1568	8.5667	-.0331	1.1471
1951	.958	13009388	12462994	.6590	5.9632	8.5748	-.0343	1.1091
1952	.962	13700311	13179699	.6443	5.9904	9.1112	.0708	1.0711
1953	.963	14364079	13832608	.6352	6.3044	8.8233	.0351	1.1470
1954	.930	15058278	14004199	.6392	6.7830	9.3442	.1075	1.1873
1955	.944	15736468	14855226	.6711	7.8811	9.8338	-.0199	1.3149
1956	.948	16645786	15780205	.6645	7.9497	10.2701	-.0275	1.2888
1957	.946	17541236	16594009	.6624	7.9843	10.7872	.0308	1.2533
1958	.915	18088306	16550800	.6783	8.7537	11.8046	.0911	1.2919
1959	.932	18484620	17227666	.7024	9.6816	11.8876	-.0025	1.4096
1960	.931	18980957	17671271	.6926	9.8224	12.1792	.0227	1.4061
1961	.917	19469717	17853731	.6934	10.1651	12.3761	.0473	1.4380
1962	.931	19950688	18574090	.7038	10.8090	12.5994	.0690	1.5060
1963	.930	20485096	19051139	.7174	11.6908	12.7153	.0477	1.6100
1964	.936	21197400	19840766	.7264	12.4037	12.8919	.0415	1.6867
1965	.944	22252206	21006082	.7327	13.2575	13.3119	.0261	1.7567
1966	.953	23630292	22519668	.7295	13.7053	13.4323	-.0251	1.8025
1967	.952	24909490	23713835	.7219	13.5987	13.7575	*.0000	1.7573

TABLE G-11

29 PETROLEUM AND COAL PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	8379654	7793088	.5296	4.7866	18.5673	.1616	1.0000
1950	.933	8548449	7975703	.6024	5.7763	18.9152	.0925	1.1616
1951	.958	8873733	8501084	.6389	6.4030	19.0859	-.0545	1.2690
1952	.962	9164507	8816256	.6045	6.2711	20.1398	.0417	1.1999
1953	.963	9421548	9072951	.5923	6.4823	19.8403	-.1089	1.2499
1954	.930	9683277	9005448	.5686	6.5420	24.7763	.1719	1.1139
1955	.944	9919532	9364038	.6312	8.0894	25.6498	.0697	1.3054
1956	.948	10283878	9749117	.6504	8.9195	26.6374	-.0896	1.3963
1957	.946	10619664	10046202	.6178	8.3022	27.2760	-.1717	1.2712
1958	.915	10729338	9817345	.5566	7.1839	28.0042	.1179	1.0529
1959	.932	10740730	10010360	.6103	8.4160	29.5165	.0975	1.1770
1960	.931	10802155	10056806	.6481	9.3540	29.6498	.0800	1.2918
1961	.917	10850226	9949657	.6694	10.5233	31.1437	.0117	1.3952
1962	.931	10885251	10134169	.6810	10.9913	32.6483	.0800	1.4116
1963	.930	10940354	10174529	.6947	12.1714	33.4839	.0079	1.5244
1964	.936	11078900	10369850	.7018	12.5262	34.4975	.0856	1.5365
1965	.944	11379209	10741973	.7336	14.6560	37.7058	.1033	1.6680
1966	.953	11820438	11264877	.7627	17.2700	40.3515	.0773	1.8403
1967	.952	12185725	11600810	.7767	19.1286	41.4315	*.0000	1.9825

TABLE G-12

30 RUBBER AND PLASTICS PRODUCTS, NEC

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	764310	710808	.4029	3.2608	1.6840	.1344	1.0000
1950	.933	908880	847985	.4837	3.8775	1.7936	-.1305	1.1344
1951	.958	1081100	1035694	.4434	3.6176	2.0409	-.0678	.9864
1952	.962	1262460	1214487	.4025	3.6119	2.3994	.0676	.9195
1953	.963	1451970	1398247	.4360	4.0221	2.6235	-.0141	.9817
1954	.930	1655040	1539187	.4438	4.3227	3.2463	.0455	.9678
1955	.944	1866770	1762231	.4436	4.5288	3.2467	-.0445	1.0118
1956	.948	2118000	2007864	.4510	4.6498	3.8606	-.0370	.9668
1957	.946	2381190	2252606	.4497	4.7442	4.4180	.1303	.9310
1958	.915	2607520	2385881	.4741	4.7988	3.4943	.0315	1.0523
1959	.932	2818200	2625562	.4810	4.9343	3.4648	-.0331	1.0854
1960	.931	3049680	2839252	.4704	4.9621	3.7680	.0198	1.0495
1961	.917	3286150	3013400	.4844	5.2422	4.0586	.0101	1.0703
1962	.931	3527280	3283898	.4788	5.2998	4.0646	.0306	1.0811
1963	.930	3784090	3519204	.4920	5.5778	4.2347	.0013	1.1142
1964	.936	4081700	3820471	.4897	5.6583	4.3487	.0527	1.1157
1965	.944	4457100	4207502	.5058	6.0768	4.4972	.0220	1.1745
1966	.953	4914000	4683042	.5106	6.3202	4.6492	-.0226	1.2003
1967	.952	5368510	5110822	.5068	6.4715	5.1089	*.0000	1.1732

TABLE G-13

31 LEATHER AND LEATHER PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	523500	486855	.3569	2.3569	.7183	.0385	1.0000
1950	.933	530180	494658	.3667	2.4350	.7056	-.0465	1.0385
1951	.958	546240	523298	.3598	2.4428	.8161	.0234	.9903
1952	.962	559770	538499	.3642	2.4800	.7976	.0503	1.0134
1953	.963	570860	549738	.3578	2.5982	.7872	.0206	1.0644
1954	.930	581850	541120	.3726	2.7044	.8305	.0457	1.0863
1955	.944	590920	557828	.3756	2.8176	.8184	.0076	1.1359
1956	.948	607160	575588	.3789	2.8800	.8504	-.0184	1.1445
1957	.946	621180	587636	.3813	2.8744	.8890	.0334	1.1234
1958	.915	621560	568727	.3962	2.9784	.8925	.0585	1.1610
1959	.932	616000	574112	.4123	3.0996	.8509	-.0127	1.2289
1960	.931	613080	570777	.3994	3.0893	.8706	.0252	1.2133
1961	.917	609140	558581	.4000	3.1744	.8741	.0238	1.2439
1962	.931	604210	562520	.4026	3.2605	.8797	.0253	1.2736
1963	.930	600120	558112	.4093	3.4029	.9174	.0702	1.3058
1964	.935	600250	561834	.4322	3.6419	.9071	.0187	1.3976
1965	.944	608600	574518	.4253	3.7281	.9165	.0408	1.4237
1966	.953	623700	594386	.4252	3.8927	.9196	.0361	1.4818
1967	.952	633920	603492	.4303	4.1267	.9664	*.0000	1.5353

TABLE G-14

32 STONE, CLAY AND GLASS PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	4029903	3747810	.4601	3.1015	4.1165	.1466	1.0000
1950	.933	4274333	3987953	.5126	3.5691	3.9821	-.0423	1.1466
1951	.958	4610948	4417289	.4867	3.4406	4.0207	-.0301	1.0981
1952	.962	4946451	4758496	.4785	3.5306	4.5387	.0495	1.0651
1953	.963	5279959	5084600	.4807	3.8786	4.9554	.0376	1.1178
1954	.930	5632308	5238046	.4929	4.1677	5.3062	.0992	1.1598
1955	.944	5986288	5651056	.5194	4.6219	5.2963	-.0049	1.2749
1956	.948	6437026	6102300	.5198	4.7421	5.6240	-.0651	1.2686
1957	.946	6892436	6520244	.5105	4.6770	6.2384	.0906	1.1860
1958	.915	7218586	6605006	.5307	5.0355	6.0095	.0684	1.2935
1959	.932	7489020	6979767	.5445	5.2776	5.7644	-.0327	1.3820
1960	.931	7804037	7265558	.5301	5.2431	6.0550	.0038	1.3368
1961	.917	8120477	7446478	.5331	5.4534	6.4805	.0101	1.3418
1962	.931	8438038	7855813	.5299	5.6297	6.7497	.0438	1.3553
1963	.930	8782756	8167963	.5439	5.9990	6.9841	.0194	1.4147
1964	.936	9209550	8620139	.5504	6.2062	7.1686	.0197	1.4421
1965	.944	9793806	9245353	.5504	6.5327	7.5861	.0180	1.4705
1966	.953	10532592	10037560	.5482	6.8324	7.9605	-.0457	1.4969
1967	.952	11240590	10701042	.5389	6.8410	8.7067	*.0000	1.4284

TABLE G-15

33 PRIMARY METAL INDUSTRIES

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	15783001	14678191	.3933	3.3023	7.3681	.2007	1.0000
1950	.933	16392516	15294218	.4771	3.9077	6.5997	.0362	1.2007
1951	.958	17327074	16599337	.4741	3.9870	6.3819	-.0715	1.2441
1952	.962	18224206	17531686	.4239	3.9349	7.2756	.1303	1.1552
1953	.963	19083229	18377150	.4546	4.4341	6.9831	-.0133	1.3058
1954	.930	19980729	18582078	.4618	4.7280	8.3738	.1659	1.2884
1955	.944	20855044	19687162	.4980	5.3597	7.5841	-.0166	1.5022
1956	.948	22033413	20887675	.4857	5.4104	8.0017	-.0581	1.4772
1957	.946	23190868	21938561	.4627	5.3436	8.8304	-.0244	1.3914
1958	.915	23885793	21855500	.4599	5.6283	10.5394	.0846	1.3574
1959	.932	24380510	22722635	.4806	6.0589	10.2384	-.0414	1.4722
1960	.931	25006118	23280696	.4569	5.8306	10.2870	-.0004	1.4112
1961	.917	25620589	23494080	.4509	6.0052	10.9975	.0224	1.4106
1962	.931	26223694	24414259	.4531	6.1433	10.9995	.0866	1.4422
1963	.930	26895878	25013167	.4932	6.7661	11.1341	.0329	1.5670
1964	.936	27800150	26020940	.4915	6.8740	10.7584	.0688	1.6186
1965	.944	29151403	27518924	.5095	7.3939	10.7928	.0580	1.7299
1966	.953	30923046	29469663	.5258	7.9511	11.0549	-.0568	1.8302
1967	.952	32561895	30998924	.5118	7.8595	12.0923	*.0000	1.7263

TABLE G-16

34 FABRICATED METAL PRODUCTS

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	5652753	5257060	.4035	3.1749	2.9969	.1414	1.0000
1950	.933	5810773	5421451	.4519	3.5092	2.6895	.0028	1.1414
1951	.958	6078968	5823652	.4413	3.5352	2.7167	-.0099	1.1446
1952	.962	6328021	6087556	.4247	3.6149	2.9287	.0654	1.1333
1953	.963	6558189	6315536	.4148	3.7543	2.7455	.0130	1.2075
1954	.930	6796008	6320287	.4211	3.9861	3.0812	.0488	1.2231
1955	.944	7020398	6627256	.4213	4.1425	3.0021	.0057	1.2829
1956	.948	7340706	6958999	.4261	4.2432	3.1366	-.0083	1.2901
1957	.946	7645726	7233803	.4230	4.2797	3.2654	.0327	1.2795
1958	.915	7794666	7132119	.4252	4.5102	3.4138	.0430	1.3213
1959	.932	7874020	7338587	.4439	4.6501	3.3130	-.0146	1.3782
1960	.931	7992677	7441182	.4282	4.6181	3.3714	.0227	1.3580
1961	.917	8104447	7431778	.4347	4.7934	3.4846	.0372	1.3888
1962	.931	8209418	7642968	.4390	4.9374	3.4211	.0608	1.4405
1963	.930	8332666	7749380	.4583	5.3211	3.5111	.0368	1.5281
1964	.936	8523550	7978043	.4601	5.4883	3.4635	.0731	1.5844
1965	.944	8845106	8349780	.4831	5.9194	3.4613	.0485	1.7002
1966	.953	9285192	8848788	.4779	6.1753	3.4118	.0272	1.7826
1967	.952	9675600	9211171	.4717	6.3776	3.4447	*.0000	1.8310

TABLE G-17

35 MACHINERY, EXCEPT ELECTRICAL

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	10737508	9985883	.4070	3.4147	3.8495	.0686	1.0000
1950	.933	10863064	10135238	.4223	3.5686	3.6232	.0403	1.0686
1951	.958	11179826	10710273	.4002	3.4743	3.1245	.0894	1.1116
1952	.962	11443604	11008747	.4238	3.8199	3.1329	.0405	1.2110
1953	.963	11656341	11225056	.4114	3.9976	3.1624	.0176	1.2600
1954	.930	11865861	11035251	.4172	4.2586	3.5383	.0288	1.2822
1955	.944	12035026	11361064	.4051	4.3341	3.4443	.0398	1.3191
1956	.948	12348787	11706650	.4053	4.4213	3.2816	.0038	1.3716
1957	.946	12615722	11934473	.4140	4.5224	3.4391	-.0496	1.3768
1958	.915	12604327	11532959	.4106	4.7079	4.3812	.0958	1.3085
1959	.932	12471690	11623615	.4373	5.0399	4.0840	-.0087	1.4338
1960	.931	12391762	11536730	.4112	4.9599	4.0157	.0227	1.4213
1961	.917	12290361	11270261	.4094	5.1047	4.0715	.0817	1.4536
1962	.931	12168136	11328535	.4282	5.4218	3.8531	.0690	1.5724
1963	.930	12061912	11217578	.4471	5.7399	3.7345	.1147	1.6809
1964	.936	12039300	11268785	.4776	6.2610	3.4890	.0766	1.8737
1965	.944	12179697	11497634	.4843	6.5881	3.3029	.1096	2.0171
1966	.953	12452454	11867189	.5018	7.1219	3.0824	-.0047	2.2382
1967	.952	12624715	12018729	.4837	7.0742	3.0698	*.0000	2.2277

TABLE G-18

36 ELECTRICAL MACHINERY

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	2377737	2211295	.4503	3.3451	1.6456	.0733	1.0000
1950	.933	2650467	2472886	.4748	3.5870	1.6246	-.0374	1.0733
1951	.958	2990892	2865274	.4450	3.4531	1.6200	.0533	1.0331
1952	.962	3342899	3215869	.4547	3.6654	1.6371	.0408	1.0881
1953	.963	3704891	3567801	.4382	3.8108	1.6278	.0128	1.1324
1954	.930	4091052	3804678	.4663	4.2200	2.0149	-.0269	1.1469
1955	.944	4489112	4237722	.4426	4.1971	2.1118	.0007	1.1161
1956	.948	4971934	4713394	.4349	4.2747	2.1985	.0036	1.1169
1957	.946	5472004	5176516	.4538	4.4709	2.4232	.0483	1.1209
1958	.915	5879654	5379884	.4607	4.7122	2.4387	.0685	1.1750
1959	.932	6247780	5822931	.4764	4.9435	2.3288	-.0215	1.2556
1960	.931	6658363	6198936	.4456	4.8168	2.3054	.0188	1.2286
1961	.917	7075963	6488658	.4374	4.9678	2.3667	.0505	1.2518
1962	.931	7500042	6982539	.4520	5.2223	2.3571	.0534	1.3150
1963	.930	7953924	7397149	.4542	5.6254	2.4560	.0163	1.3853
1964	.936	8489250	7945938	.4705	5.9326	2.6641	.0488	1.4079
1965	.944	9180194	8666103	.4907	6.2260	2.6548	.0552	1.4766
1966	.953	10030608	9559169	.4895	6.5632	2.6344	-.0058	1.5580
1967	.952	10867370	10345736	.4795	6.7117	2.7937	*.0000	1.5490

TABLE G-19

37 TRANSPORTATION EQUIPMENT

YEAR	STOCK ADJ	CAPITAL STOCK	EMPLOYED CAP	CAP SHARE	OUTPUT/ HOUR	CAP/ HOUR	CHANGE IN A	A(T)
1949	.930	10612915	9870011	.4190	3.5610	4.3246	.1177	1.0000
1950	.933	10797711	10074264	.4525	3.9071	4.0435	-.0672	1.1177
1951	.958	11177777	10708311	.3802	3.4676	3.5732	.0917	1.0426
1952	.962	11511253	11073826	.3836	3.6621	3.2445	.1115	1.1382
1953	.963	11799552	11362969	.3817	3.9097	2.8824	.0501	1.2651
1954	.930	12090843	11244484	.4043	4.2992	3.2249	.1192	1.3284
1955	.944	12347408	11655953	.4344	4.7761	3.0774	-.0610	1.4868
1956	.948	12759962	12095444	.4002	4.6162	3.2761	.0452	1.3961
1957	.946	13133076	12423890	.4249	4.7970	3.2160	-.0500	1.4592
1958	.915	13223462	12099457	.4004	4.9124	3.8887	.0773	1.3862
1959	.932	13190870	12293891	.4201	5.1770	3.6499	.0372	1.4933
1960	.931	13213005	12305962	.4233	5.4485	3.7630	.0220	1.5489
1961	.917	13226834	12129007	.4230	5.6969	3.9653	.1163	1.5830
1962	.931	13217829	12305798	.4605	6.2179	3.6822	.0742	1.7671
1963	.930	13231146	12304966	.4791	6.6474	3.6073	.0346	1.8982
1964	.936	13342700	12488767	.4807	6.9147	3.6384	.1040	1.9638
1965	.944	13644991	12880872	.5089	7.5392	3.4849	.0069	2.1680
1966	.953	14110362	13447175	.4732	7.4749	3.3816	-.0208	2.1831
1967	.952	14478535	13783565	.4602	7.5231	3.5879	*.0000	2.1377